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Tanaka

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(54) **COMPILER, COMPILATION METHOD, AND COMPILATION PROGRAM**

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G06F 9/45 (2006.01)

(52) **U.S. Cl.** **717/151**; 717/140

(58) **Field of Classification Search** None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

- 6,035,122 A * 3/2000 Ando 717/155
- 6,170,083 B1 * 1/2001 Adl-Tabatabai 717/158
- 6,463,582 B1 * 10/2002 Lethin et al. 717/158
- 6,681,387 B1 1/2004 Hwu et al.
- 2002/0066080 A1 5/2002 O'Dowd
- 2003/0233643 A1 * 12/2003 Thompson et al. 717/161

OTHER PUBLICATIONS

Fisher et al.; "Trace Scheduling: A Technique for Global Microcode Compaction"; *IEEE Transactions on Computers*; c. 1981; pp. 478-490; vol. C-30, No. 7.

Hwu et al.; "The Superblock: An Effective Technique for VLIW and Superscalar Compilation"; *The Journal of Supercomputing*; No. 7; pp. 229-248; c. 1993.

A.V. Aho et al., "Compilers: Principles, Techniques, and Tools, Chapter 10—Code Optimization," Addison Wesley (1986).

Ikuo Nakata, Konpaira no Kosei to Saitekika (Compiler Configuration & Optimization), Asakura Shuppan (2004), pp. 358-381.

* cited by examiner

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(57) **ABSTRACT**

A compile converts a program having a multiple execution paths so as to expand a basic block on a specific execution path while maintaining the program integrity. The compiler generates new basic blocks B103 and B104. The basic block B104 is composed of (i) statements generated by replacing replacement target variables in a partial source program (basic blocks B1-B7) on a hot path 200, and (ii) a branch instruction that includes a branch condition for executing the hot path, generated by modifying a branch instruction on the hot path 200. The basic block B103 is composed of statements for restoring restoration target variables out of the replacement target variables. The source program is then converted to execute, subsequently to the basic block B104, the basic block B103 if the branch instruction in the basic block B103 is true, and to execute the basic block B1 if false.

18 Claims, 15 Drawing Sheets

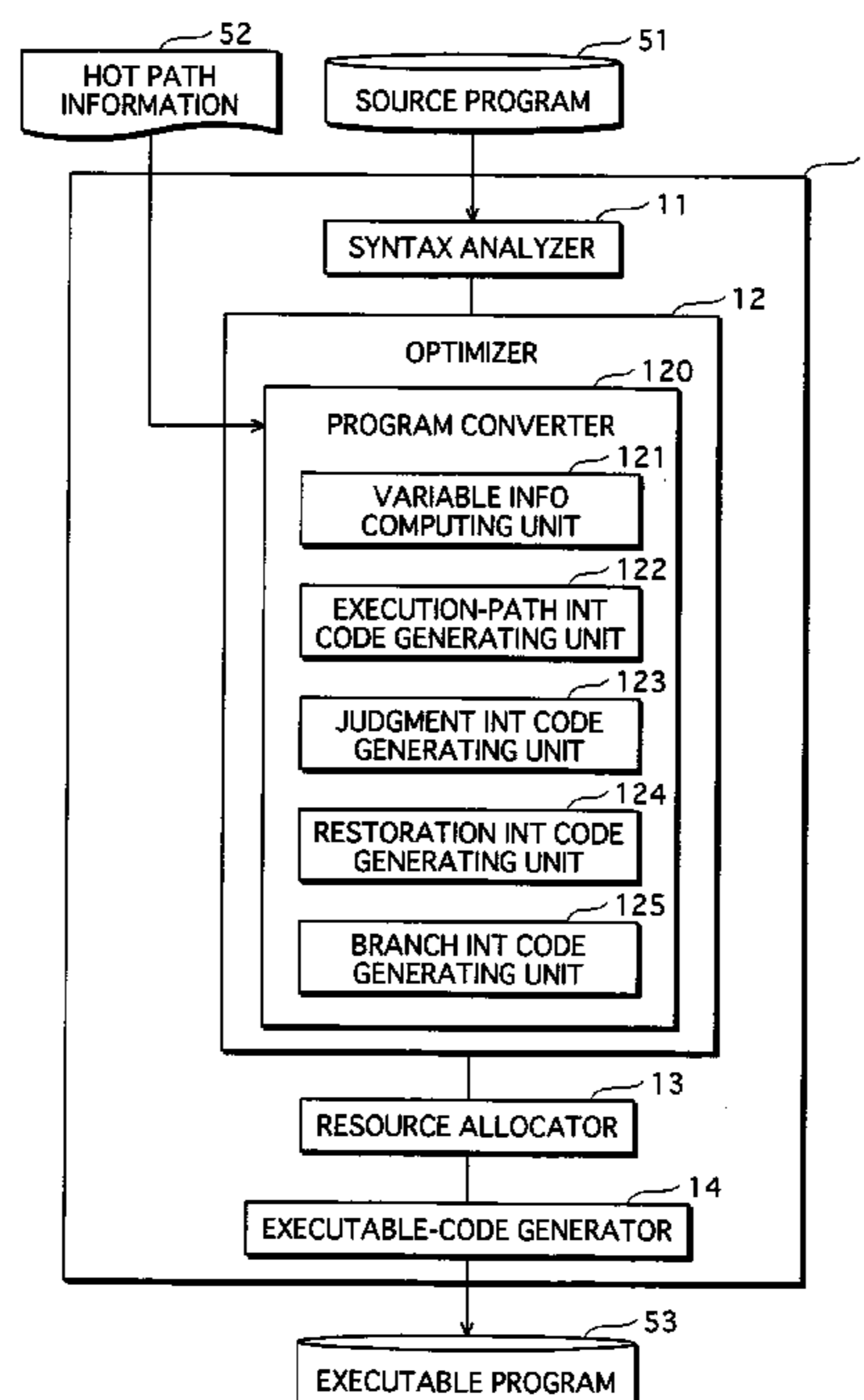


FIG. 1

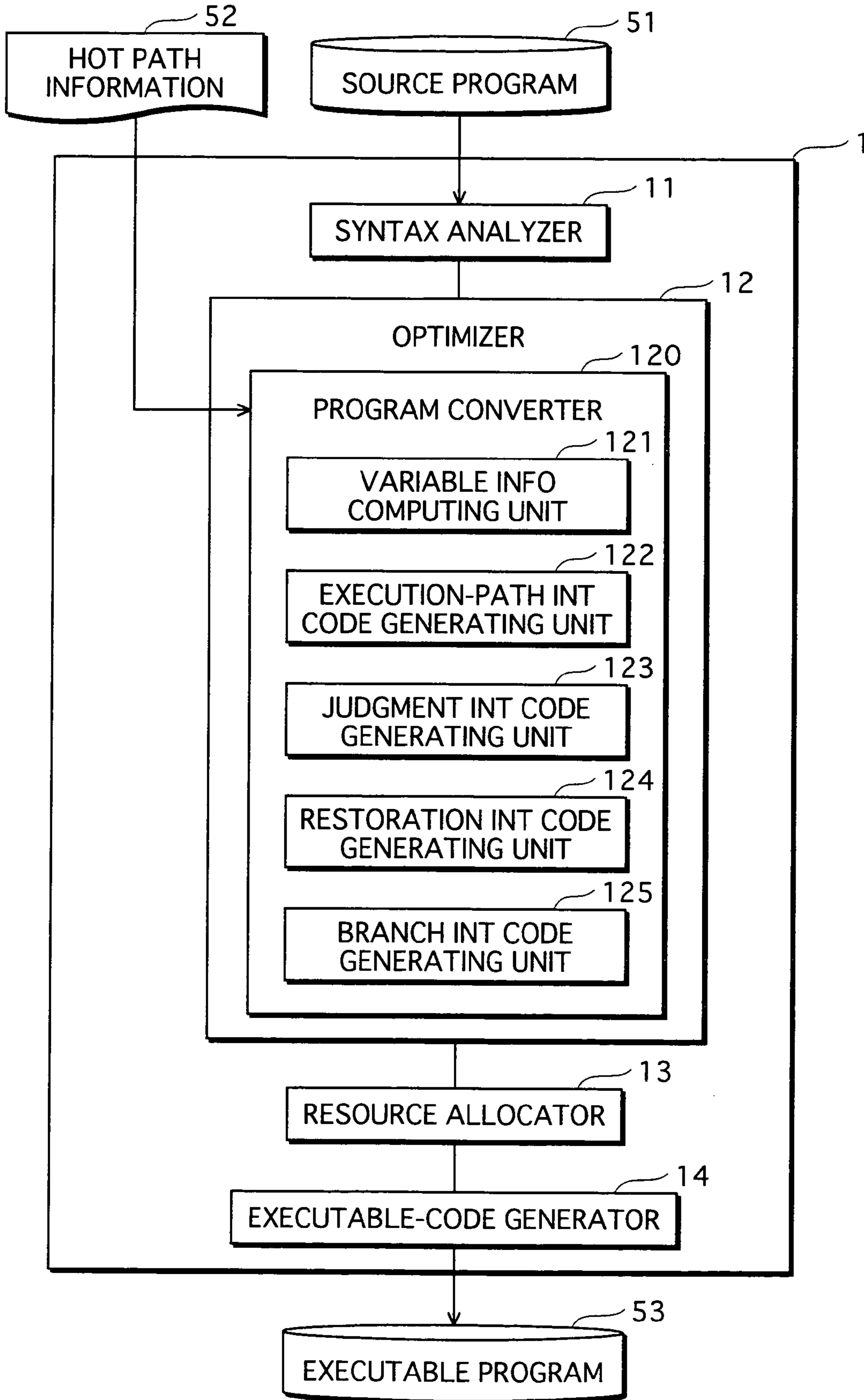


FIG. 2

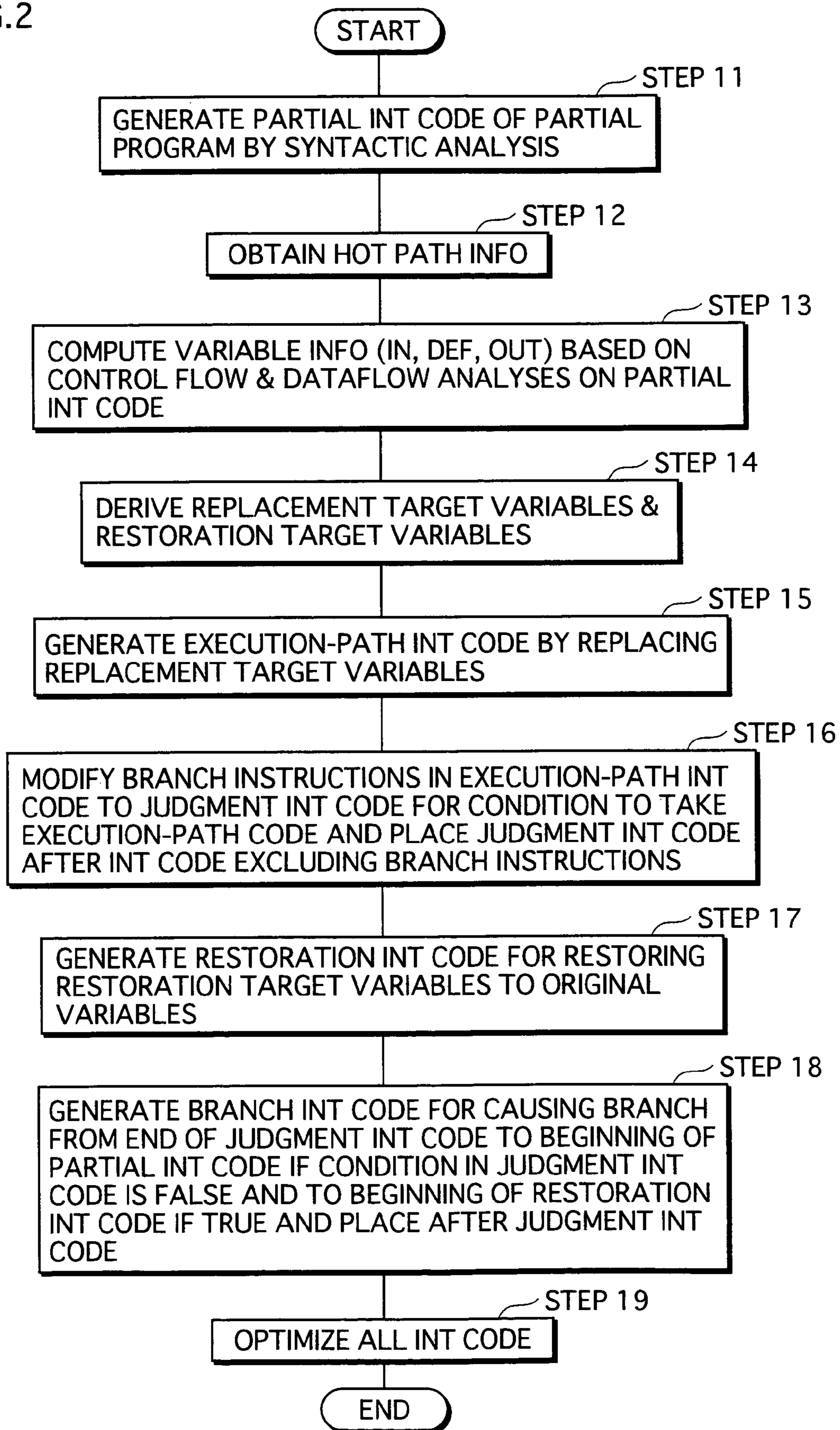


FIG.3

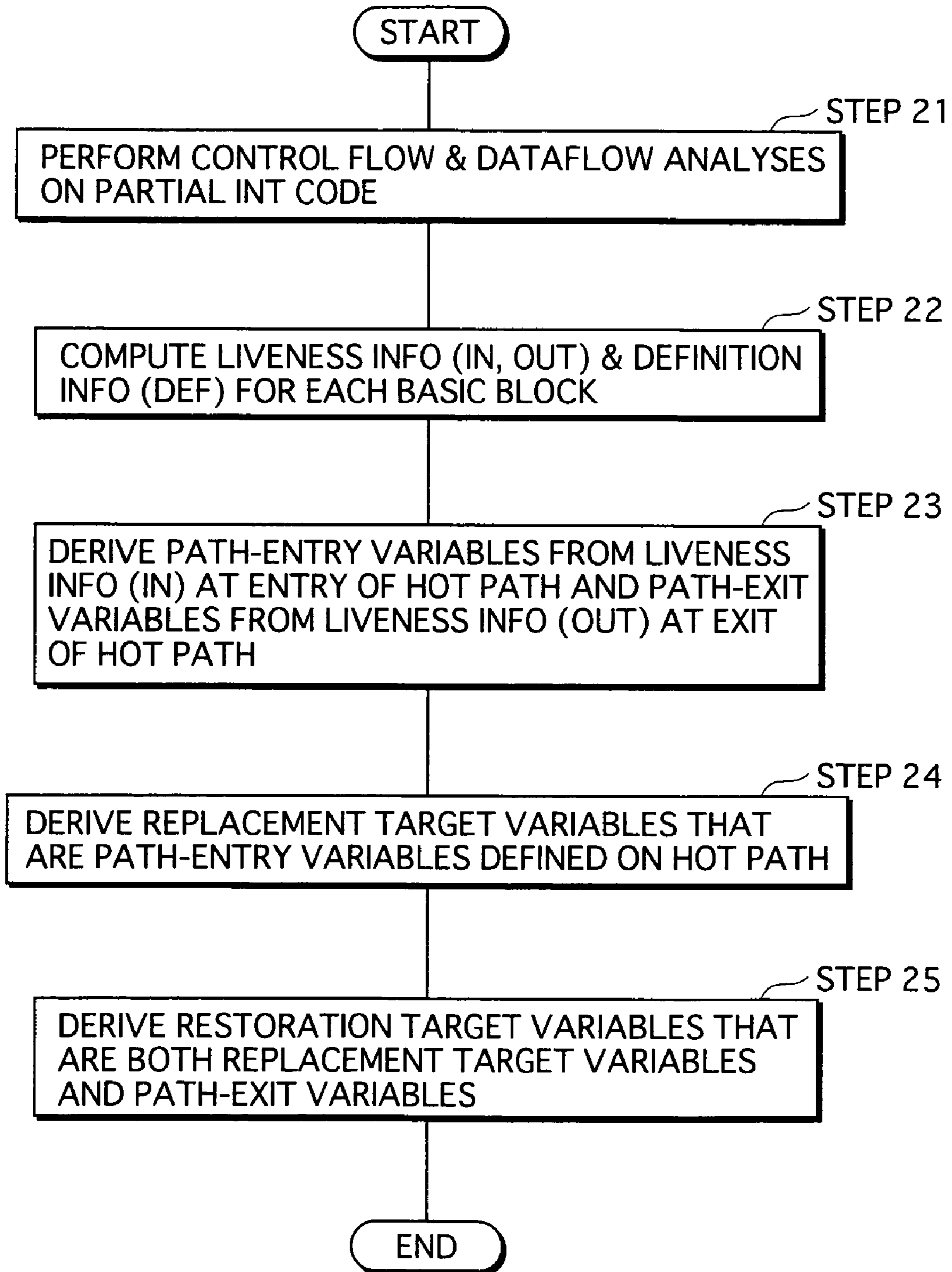


FIG.4

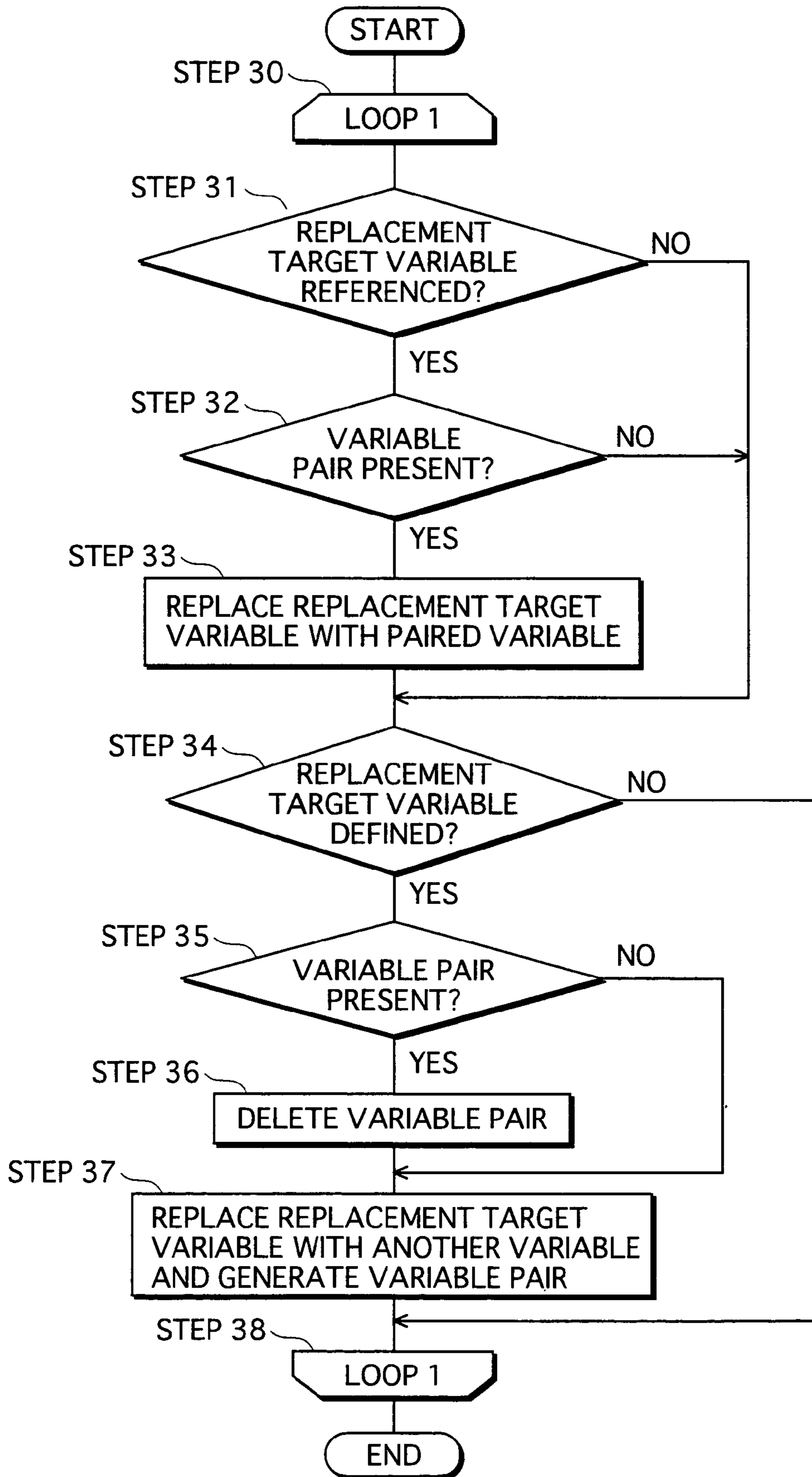


FIG. 5A

```

.....
a = b + c; /* S1 */
c = a + 10; /* S2 */
If (c > 0){ /* S3 */
    c = c + 1; /* S4 */
    d = e + 1; /* S5 */
} else {
    a = c + 2; /* S6 */
    d = d + 2; /* S7 */
}
}
f = d + 3; /* S8 */
If (f > 0){ /* S9 */
    a = b + 10; /* S10 */
    x = y + 20; /* S11 */
} else {
    b = a + 10; /* S12 */
    x = y + 30; /* S13 */
    g = c + b; /* S14 */
}
f = f + g; /* S15 */
.....
    
```

FIG. 5B

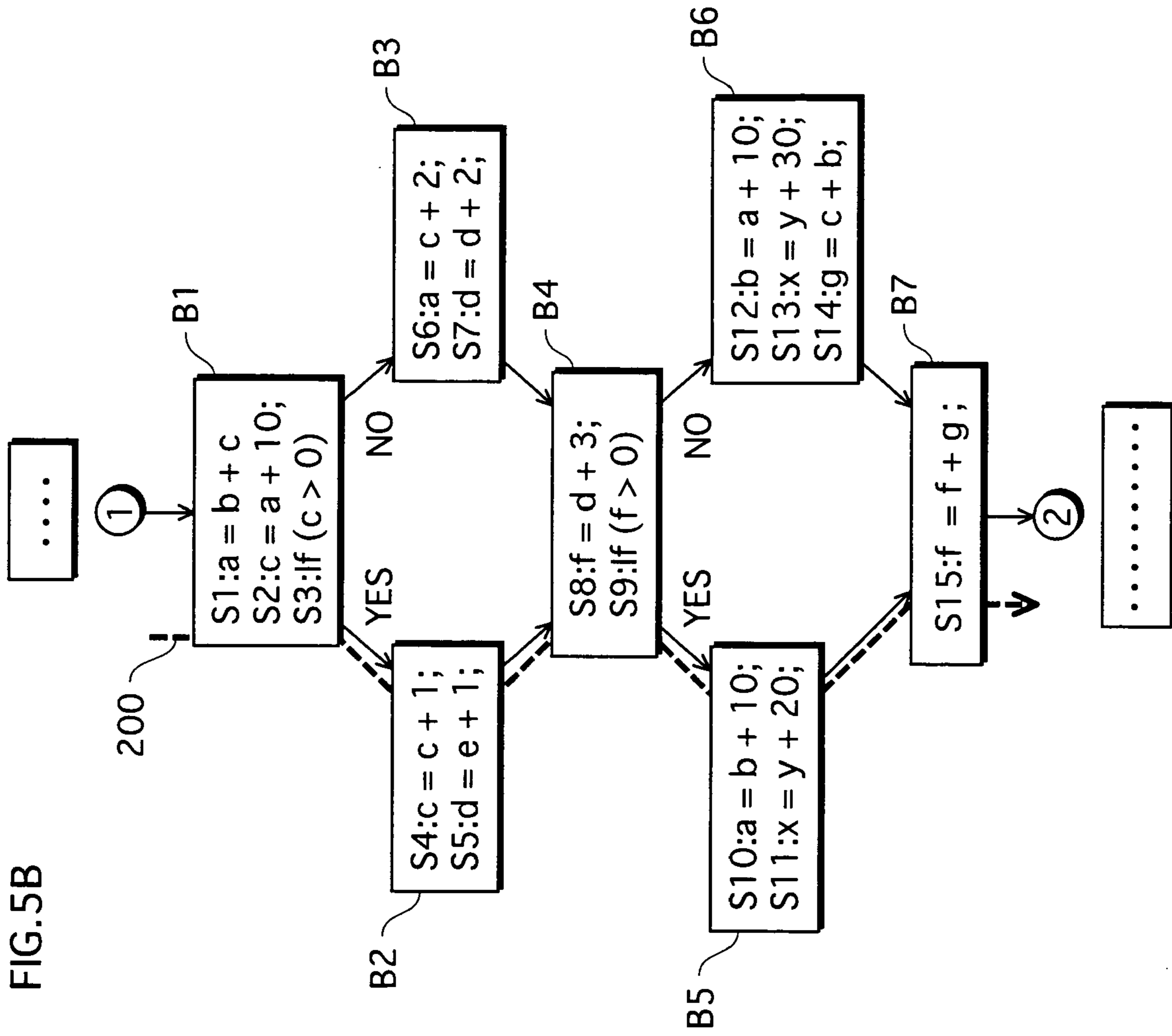


FIG. 6

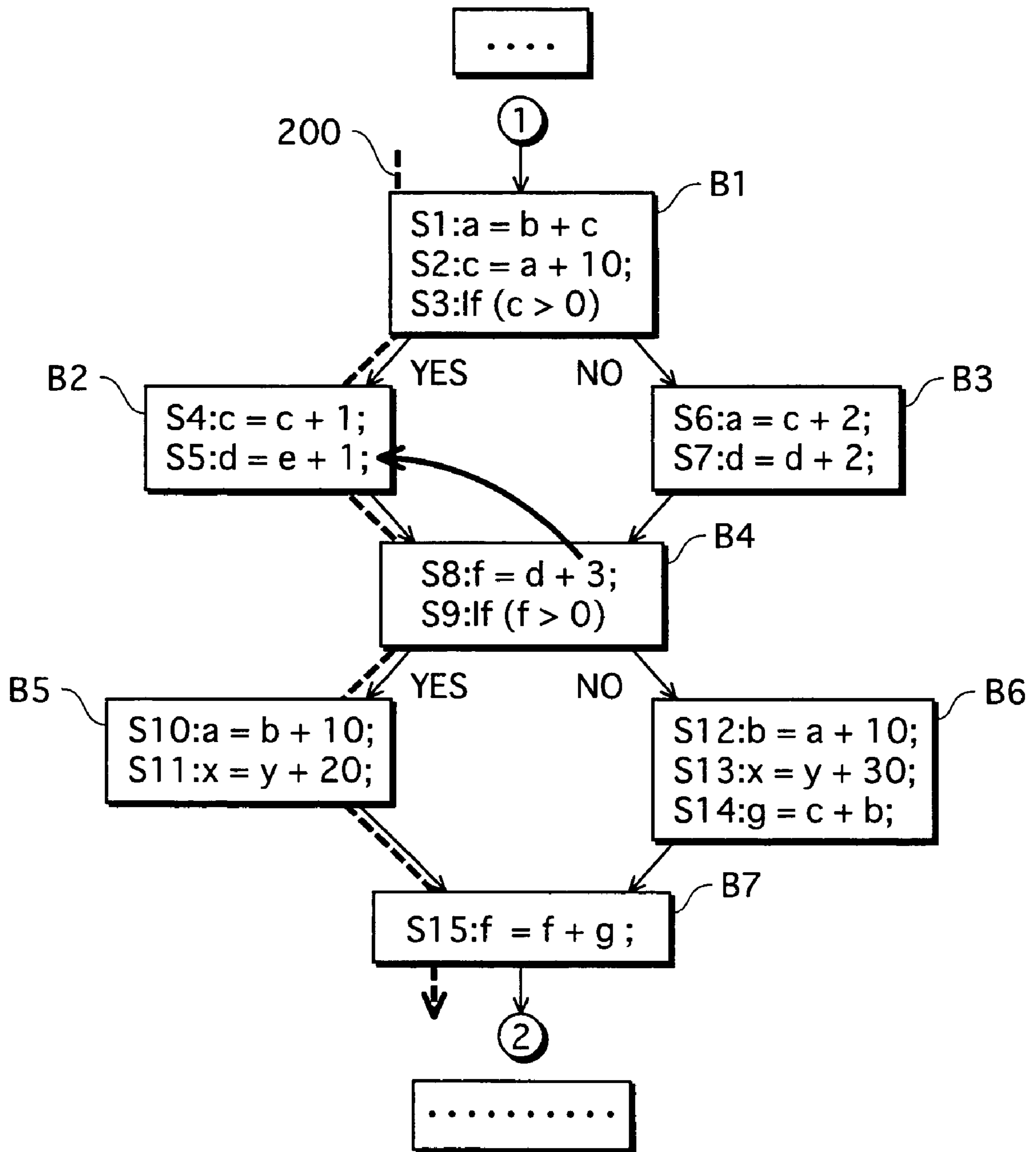


FIG. 7

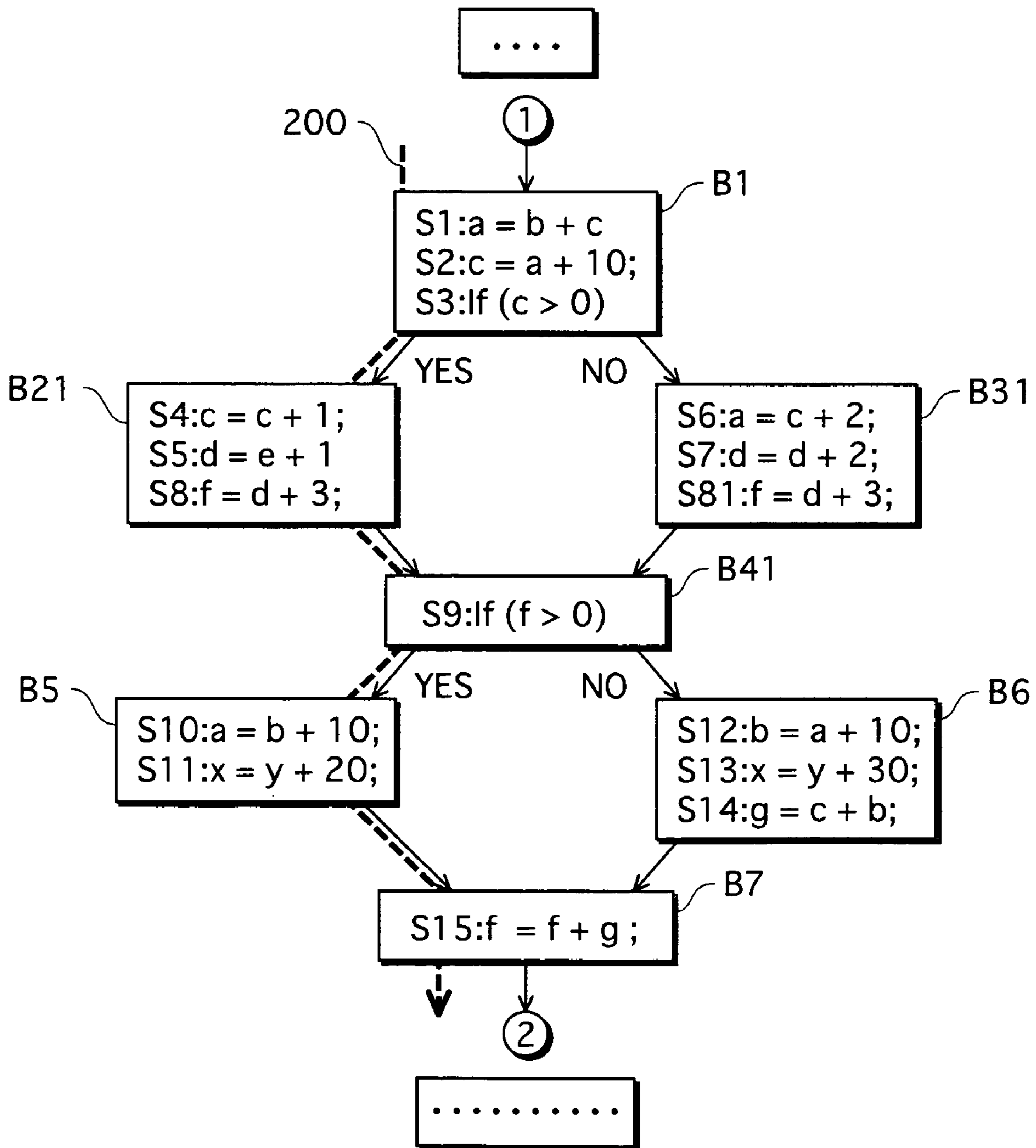


FIG. 8

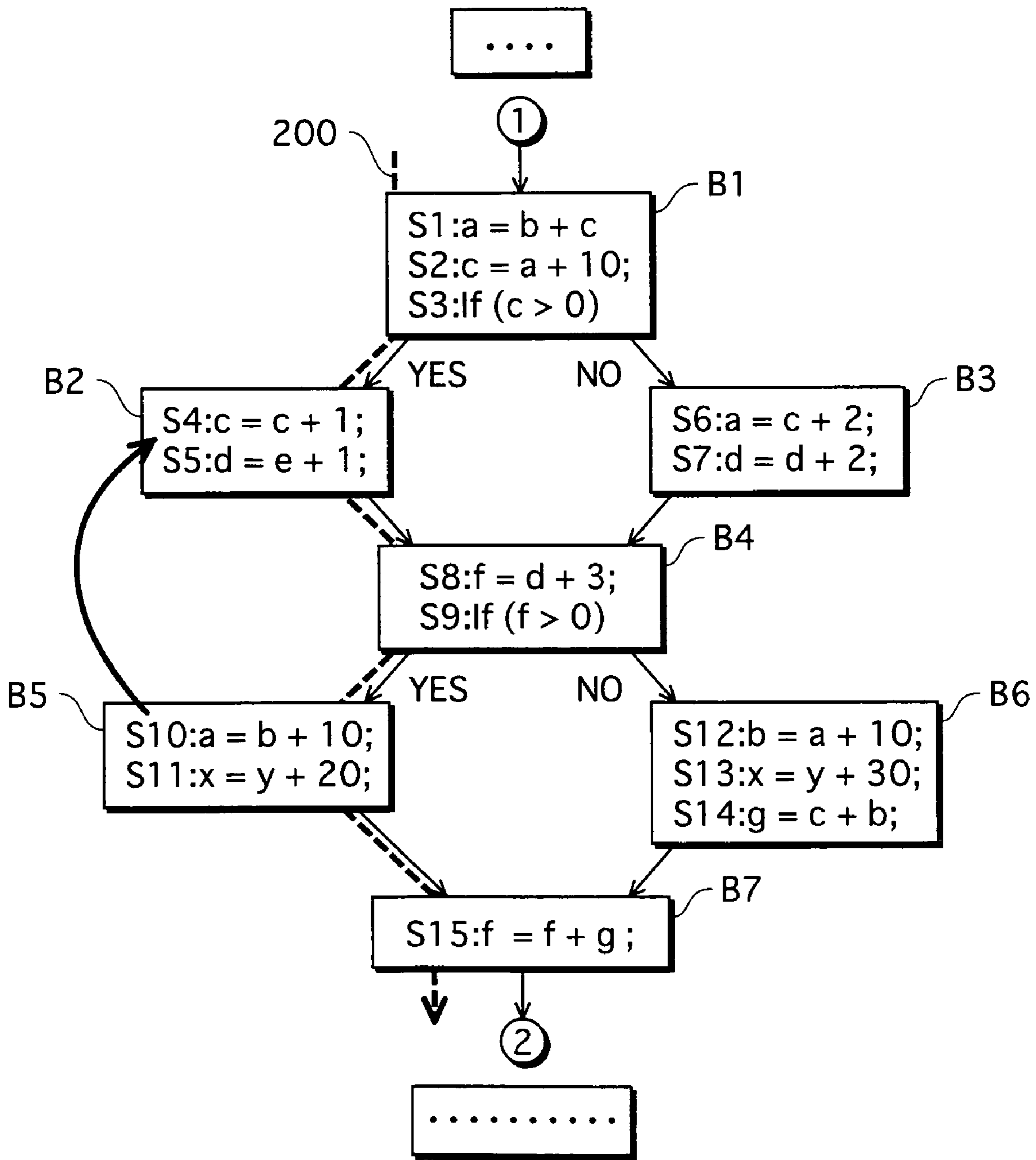


FIG.9

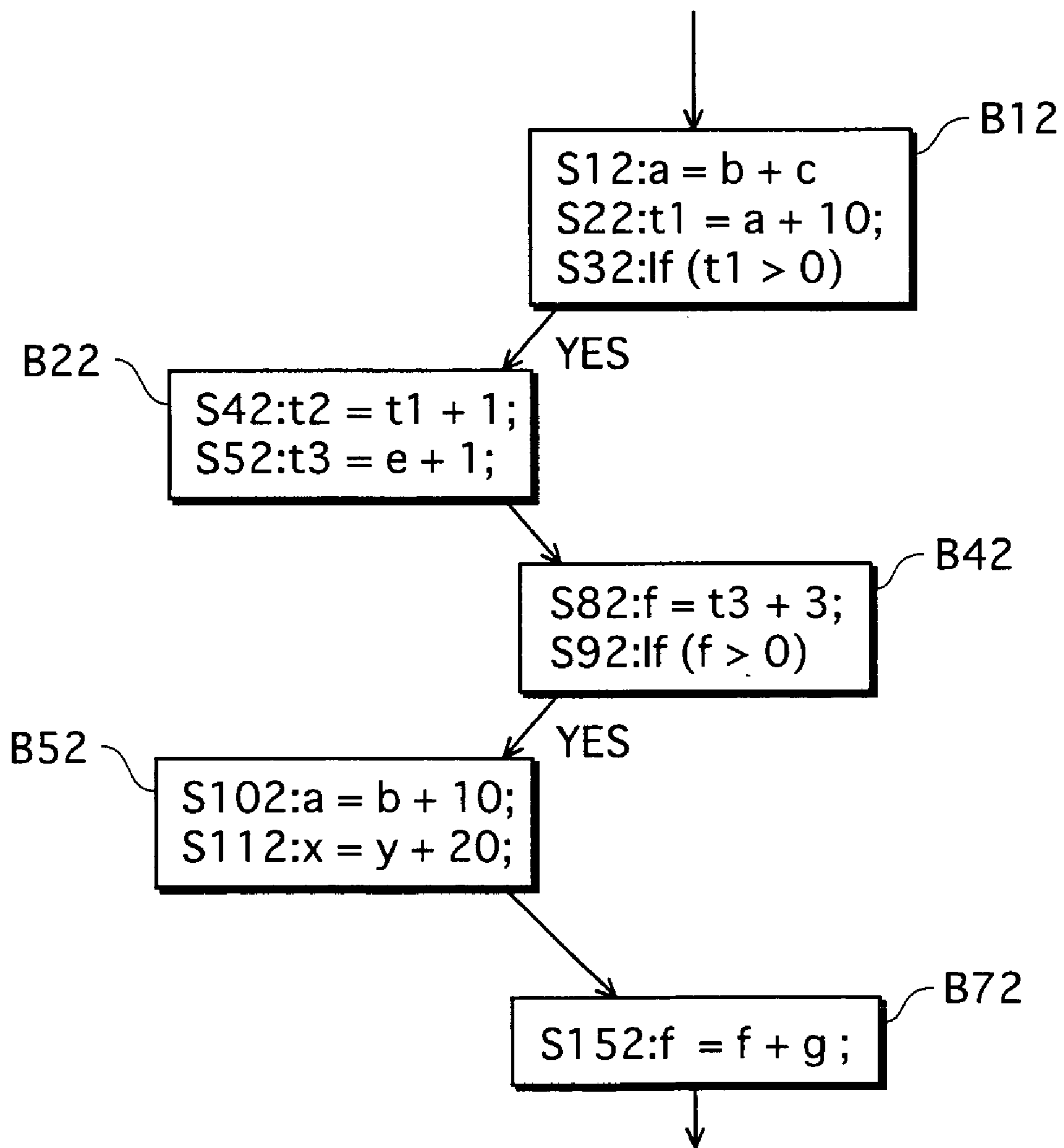


FIG. 10A

301 BLOCK	302 IN	303 DEF	304 OUT
B1	b,c,d,e,g,z,w,y	a,c	a,b,c,d,e,g,z,w,y
B2	a,b,c,e,g,z,w,y	c,d	a,b,c,d,e,g,z,w,y
B3	b,c,d,e,g,z,w,y	a,d	a,b,c,d,e,g,z,w,y
B4	a,b,c,d,e,g,z,w,y	f	a,b,c,e,f,g,z,w,y
B5	b,c,e,f,g,z,w,y	a,x	a,c,e,f,g,z,w,x,y
B6	a,c,e,f,z,w,y	b,x,g	a,c,e,f,g,z,w,x,y
B7	a,c,e,f,g,z,x,y	f	a,c,e,f,z,w,x,y

FIG. 10B

401	PATH-ENTRY VARIABLE	b,c,d,e,g,z,w,y
402	PATH-EXIT VARIABLE	a,c,e,f,z,w,x,y
403	REPLACEMENT TARGET VARIABLE	c,d
404	RESTORATION TARGET VARIABLE	c

FIG. 10C

501 BLOCK	502 VARIABLE PAIR GENERATION HISTORY
B12	(c,t1)
B22	(c,t2) (d,t3)
B42	(c,t2) (d,t3)
B52	(c,t2) (d,t3)
B72	(c,t2) (d,t3)

FIG. 11

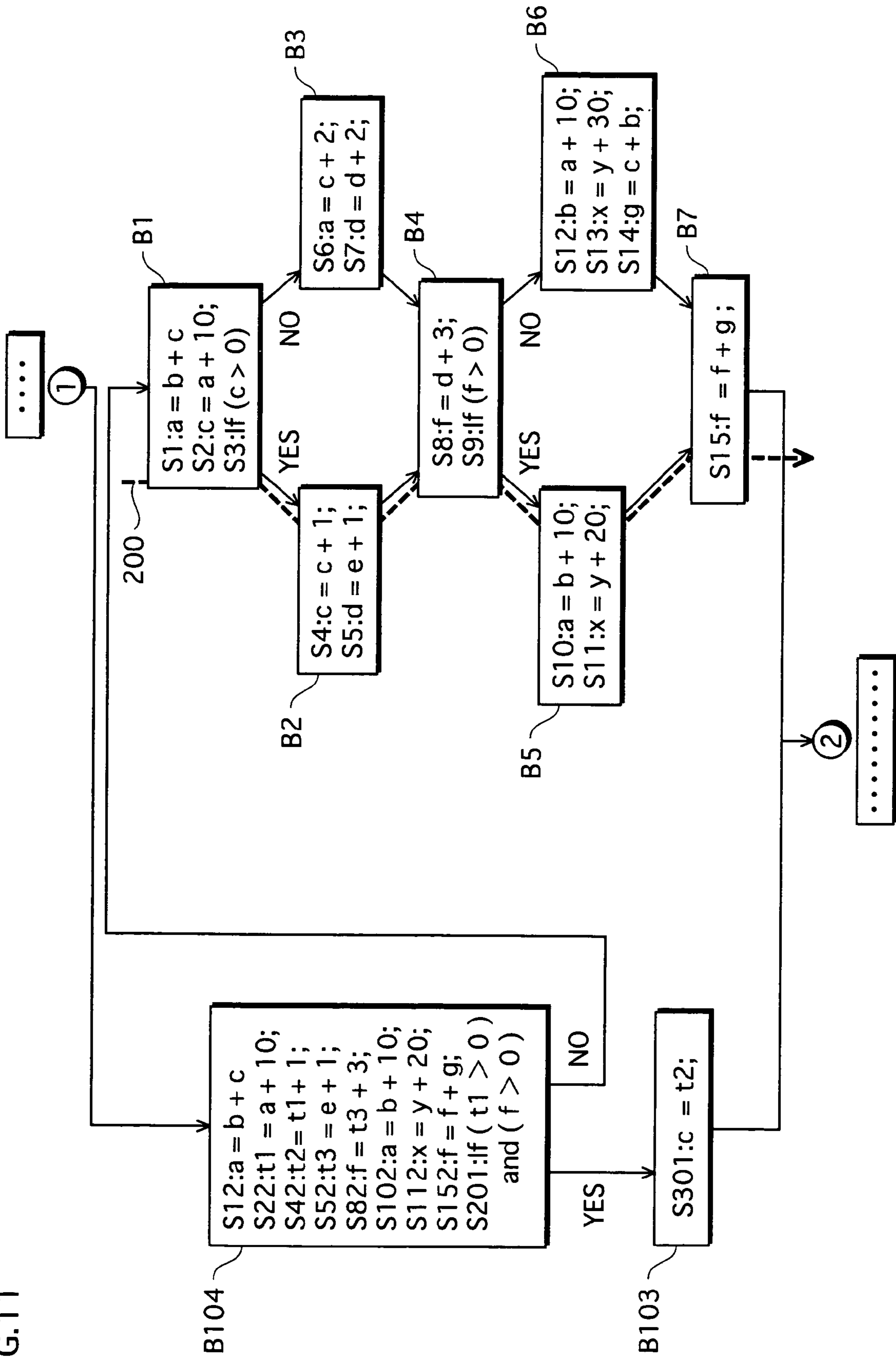
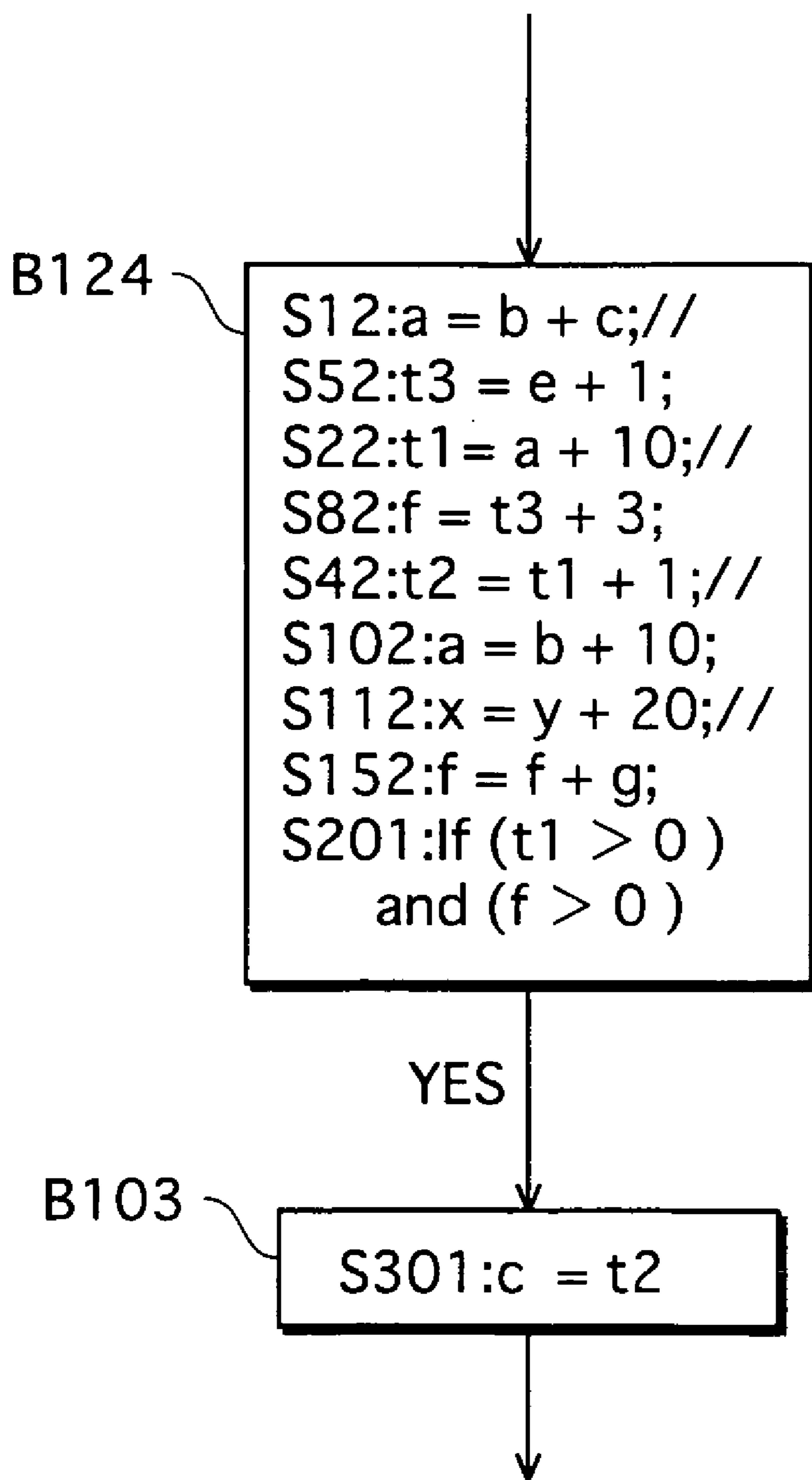
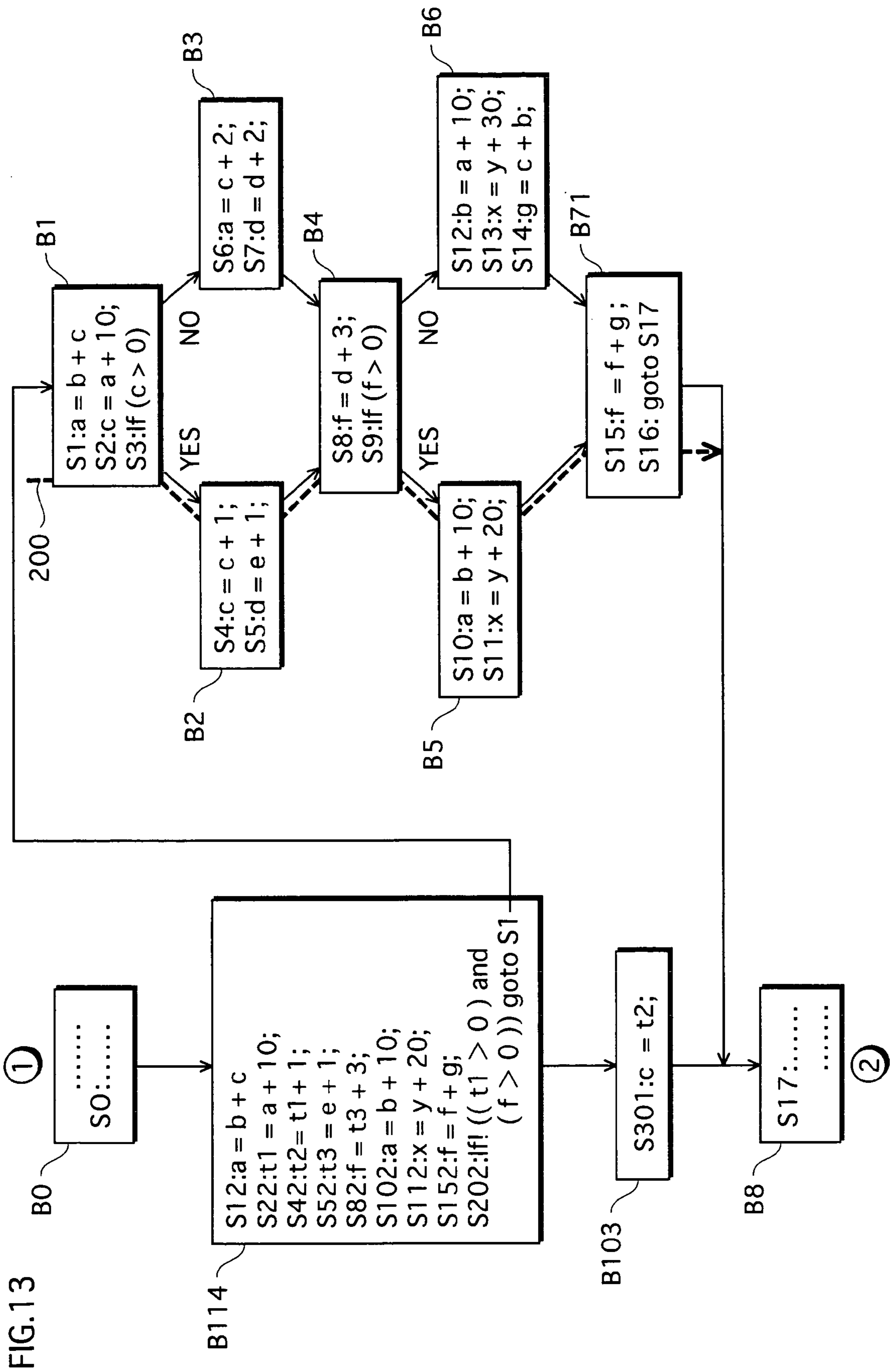


FIG. 12





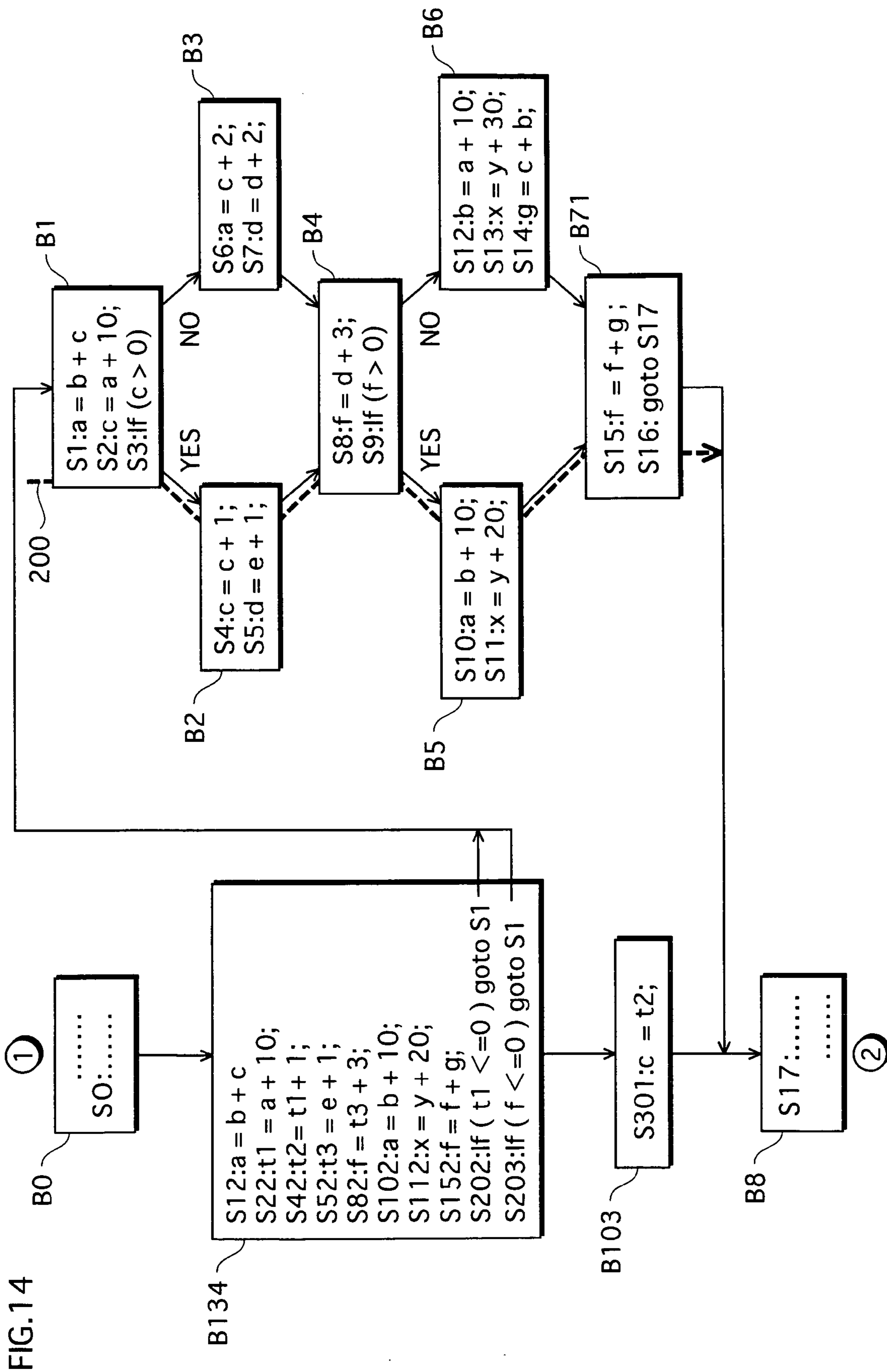
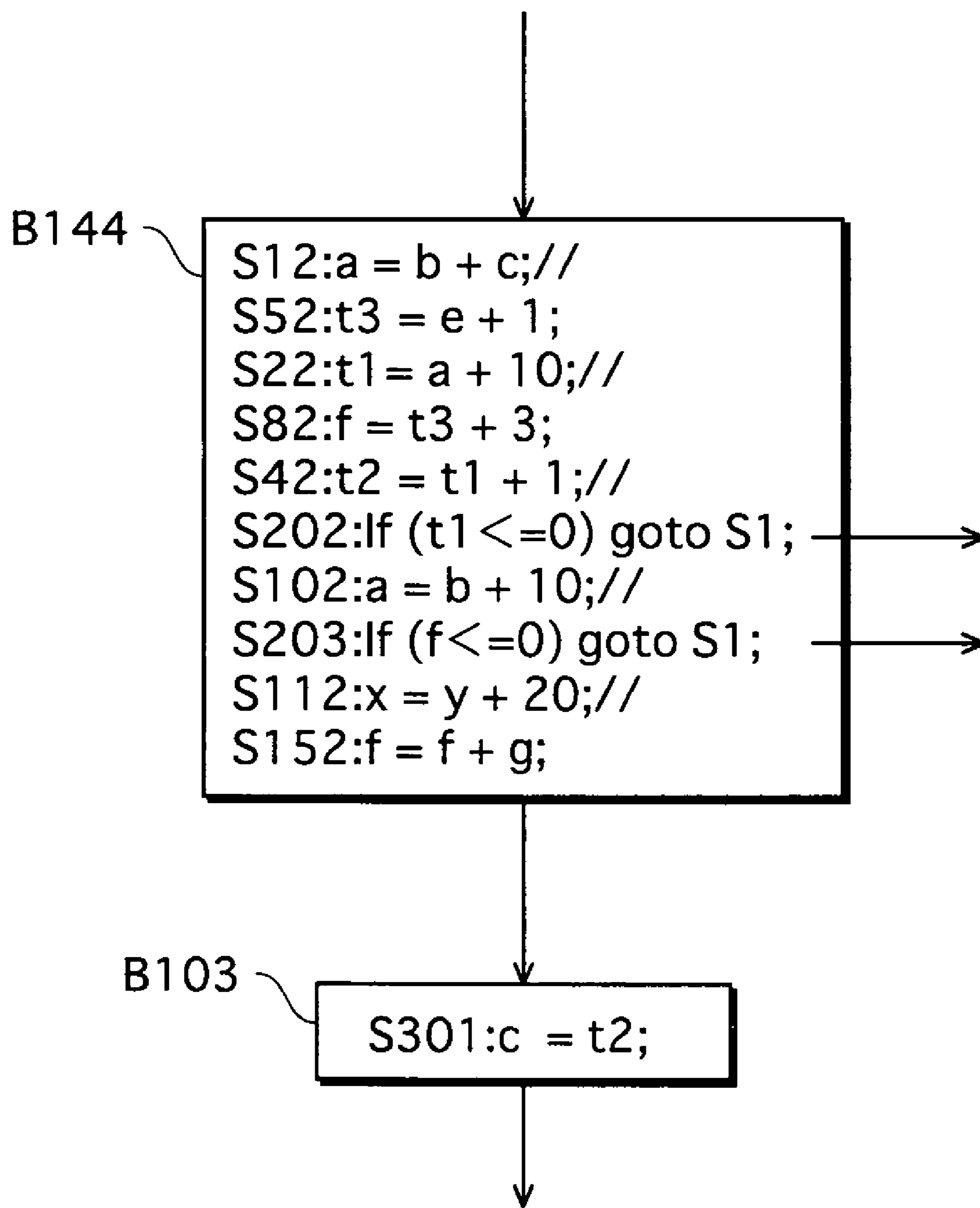


FIG. 15



COMPILER, COMPILATION METHOD, AND COMPILATION PROGRAM

This application is based on an application No. 2004-275573 filed in Japan, the content of which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

The present invention relates to compilers, and more specifically to an optimizing compilation technique for improving execution speeds.

(2) Description of the Related Art

Conventionally, in order to improve the performance of programs installed in a computer system that processes massive data, an optimizing compiler is used to optimize such a program to shorten the program execution time.

One optimization method is instruction scheduling that reorders program statements to improve the execution efficiency.

Upon the optimization, a compiler analyzes the control flow of a program focusing on branches and branch targets to divide the program into units called basic blocks. A basic block is a sequence of consecutive statements containing no branches and merges, and thus executed from the beginning to the end in order. Yet, each basic block may contain a branch at the end.

Since basic blocks contain no branches and merges in a middle, instruction scheduling within each basic block is readily carried out. It should be noted, however, that the local optimization within basic blocks produces only a limited effect. For this reason, it is desirable to expand basic blocks, so that instruction scheduling takes place within a wider range of the program.

Regarding a program containing multiple branches, it may be known that which of the execution paths is frequently executed (such an execution path is hereinafter referred to as a "hot path"). According to one known method, statements on a hot path are moved so as to expand a basic block to increase the execution efficiency of the hot path (See "Compiler Configuration & Optimization" by Ikuo NAKATA, Published by Asakura Shuppan in 2004, pp. 358-381).

Here, a description is given to how to expand a basic block residing on a hot path, taking a program shown in FIG. 5A as an example. FIG. 5A shows part of the program, whereas FIG. 5B shows a control flow graph, which is a representation of the control flow, of the program. In the graph, edges connecting basic blocks B1-B7 represent branches and merges. In this example, an execution path represented by a dashed line that sequentially connects the basic blocks B1, B2, B4, B5 and B7 is a hot path.

As shown in FIG. 6, a statement S8 included in the basic block B4 is moved into the basic block B2. Next, for a path branched from the basic block B3 to the basic block B4, a statement S81 is generated by duplicating the statement S8 and inserted into the basic block B3 (FIG. 7). With this arrangement, the basic block B2 residing on the hot path is expanded while maintaining the program integrity.

However, there is a problem in a case shown in FIG. 8 where a statement S10 is moved from the basic block B5 to the basic block B2. Suppose, an execution path is taken sequentially from the basic blocks B1, B2, and B4, and a branch condition of a statement S9 in the basic block B4 is false. In this case, a variable "a" referenced by a statement S12 in the basic block B6 must hold a value defined by a statement S1 in the basic block B1. However, the variable "a"

holds a value defined by the statement S10 having been moved into the basic block B2. As a result, the program integrity is no longer maintained.

As described above, there may be a case where data dependency present in a program may not be ensured if a statement is moved across a basic block of which last statement is a branch instruction. In such a case, reordering of the statements is restricted and thus the basic blocks cannot be expanded.

SUMMARY OF THE INVENTION

The present invention is made in view of the above problems and aims to provide a compiler for allowing a basic block on a specific execution path to be expanded, while maintaining the program integrity.

According to one aspect of the present invention, there is provided a compiler for converting a source program including a branch instruction into an object program composed of lines of object code. The compiler includes: an execution path specifying unit operable to specify one of a plurality of execution paths of a partial series of instructions, including a branch instruction, of the source program; an execution-path code generating unit operable to generate execution-path code that at least includes object code corresponding to instructions residing on the specified execution path except the branch instruction, the code generation involving replacing, with another variable, each variable that needs to be alive at an entry point of the specified execution path and is defined on the specified execution path; a restoration code generating unit operable to generate restoration code for restoring each of the replaced variables that needs to be alive at an exit point of the specified execution path to an original variable; a partial code generating unit operable to generate partial code corresponding to the partial series of instructions; and a branch code generating unit operable to generate branch code based on a branch condition of the branch instruction residing on the specified execution path. The branch code leads from an end of the execution-path code to a beginning of the restoration code if the branch condition is true, and causes a branch from the end of the execution-path code to a beginning of the partial code if the branch condition is false.

Note that the end of the execution-path code is lead to the beginning of the restoration code as a result of sequential execution of the code or as a result of a branch.

With the structure stated above, a basic block residing on the specified execution path is expanded. Consequently, instruction scheduling can take place within a wider range of code, so that optimization is performed more effectively. With the structure stated above, in addition, the statements on the specified execution path are executed with a higher priority and include no branch instructions. Consequently, the execution speed of the execution-path code improves, especially when the specified execution path is taken highly frequently than other paths.

As described above, the compiler according to the present invention is capable of converting a program including a multiple execution paths, in a manner to increase the execution speed of a frequently executed path. For this advantage, the compiler is highly usable for example by being installed in information processing devices including digital home appliances.

Here, the execution-path code generating unit may be further operable to place the execution-path code at a position immediately after a series of instructions immediately preceding a beginning of the partial series of instructions. The restoration code generating unit may be further operable to place the restoration code at a position immediately after the end of the execution-path code and to place, at a position

immediately after the restoration code, a series of instructions immediately following an end of the partial series of instructions. The branch code generating unit may be further operable to generate branch code that causes a branch from an end of the partial code to the series of instruction immediately following the end of the partial series of instructions.

With the structure stated above, the newly generated execution-path code is placed so as continuously follow the source program excluding the partial series of instructions. Thus, when executing the source program, the cache memory is effectively allocated. In addition, since there is no branch between the execution-path code and the source program, the execution speed of the overall program improves, especially when the specified execution path is taken highly frequently.

Here, the compiler may convert the source program into intermediate code based on a syntactic analysis, and convert the intermediate code into the object program. The execution-path code generating unit may include: a variable information deriving subunit operable to derive a target variable to be replaced, from variables included in partial intermediate code that is converted from the partial series of instructions based on the syntactic analysis; an execution-path intermediate code generating subunit operable to generate execution-path intermediate code at least including intermediate code that is included in the partial intermediate code and corresponds to the instructions residing on the specified execution path except the branch instruction, by replacing each target variable included in the intermediate code with another variable; and a judgment intermediate code generating subunit operable to convert all branch condition included in the execution-path intermediate code into a single branch condition for taking the specified execution path and to generate judgment intermediate code for making a judgment on the branch condition. The restoration code generating unit may include a restoration intermediate code generating subunit operable to generate restoration intermediate code for restoring each replaced variable that needs to be alive at the exit point of the specified execution path to an original variable. The branch code generating unit may include: a branch intermediate code generating subunit operable to generate branch intermediate code that causes a branch to a beginning of the partial intermediate code if the branch condition in the judgment intermediate code is false; and an executable code generating subunit operable to convert the partial intermediate code, the execution-path intermediate code, the judgment intermediate code, the restoration intermediate code, and the branch intermediate code to executable code that constitutes the object program.

With the structure stated above, the source program is first converted into an intermediate program, which is easier for the compiler to process, so that an executable program is generated effectively. In addition, since the intermediate program contains a single branch instruction generated by combining a plurality of branch instructions, optimization of the intermediate program is effectively carried out.

Here, the compiler may convert the source program into intermediate code based on a syntactic analysis, and converts the intermediate code into the object program. The execution-path code generating unit may include: a variable information deriving subunit operable to derive a target variable to be replaced, from variables included in partial intermediate code that is converted from the partial series of instructions based on the syntactic analysis; an execution-path intermediate code generating subunit operable to generate execution-path intermediate code at least including intermediate code that is included in the partial intermediate code and corresponds to the instructions residing on the specified execution path except the branch instruction, by replacing each target variable included in the intermediate code with another variable; and a judgment intermediate code generating subunit oper-

able to separately convert each branch condition included in the execution-path intermediate code into an individual branch condition for taking the specified execution path and to generate separate sets of judgment intermediate code each for making a judgment on a respective one of the branch conditions. The restoration code generating unit may include a restoration intermediate code generating subunit operable to generate restoration intermediate code for restoring each replaced variable that needs to be alive at the exit point of the specified execution path to an original variable. The branch code generating unit may include: a branch intermediate code generating subunit operable to separately generate sets of branch intermediate code each for causing a branch to a beginning of the partial intermediate code if the branch condition in the respective one of the sets of judgment intermediate code is false and leading toward a beginning of the restoration intermediate code if the branch condition is true; and an executable code generating subunit operable to convert the partial intermediate code, the execution-path intermediate code, the judgment intermediate code, the restoration intermediate code, and the branch intermediate code to executable code that constitutes the object program.

With the structure stated above, the judgment intermediate code generating subunit separately converts each branch condition included in the execution-path code into an individual branch condition for taking the specified execution path and generates separate sets of branch intermediate code each for making a judgment on an individual one of the branch conditions. Consequently, in the case, for example, where the specified execution path is not so frequently taken, a branch to another execution path is taken at an earlier stage of program execution.

Here, the compiler may have an interpreter function for sequentially executing the source program. The compiler may further include an extracting unit operable to extract a frequently executed path by collecting information on execution paths taken during execution of the partial series of instructions using the interpreter function. The execution path specifying unit may specify the execution path extracted by the extracting unit.

With the structure stated above, an execution path that is frequently taken is specified based on information obtained through actual execution of the program. Consequently, it is allowed to expand a basic block residing on the thus specified frequently-executed path.

Here, the compiler may optimize object code generated by the partial code generating unit, the execution-path code generating unit, the restoration code generating unit, and the branch code generating unit.

With the structure stated above, the thus generated object program is optimized to further improve the execution speed.

BRIEF DESCRIPTION OF THE DRAWINGS

These and the other objects, advantages and features of the invention will become apparent from the following description thereof taken in conjunction with the accompanying drawings which illustrate a specific embodiment of the invention.

In the drawings:

FIG. 1 is a functional block diagram of a compiler according to an embodiment of the present invention;

FIG. 2 shows the operation flow of the compiler;

FIG. 3 shows the flow of variable information computing processing performed by a variable information computing unit 121;

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FIG. 4 shows the flow of variable replacement processing performed by an execution-path intermediate code generating unit 122;

FIGS. 5A and 5B are views for used for explaining the operation of the compiler;

FIG. 6 is a view used for explaining prior art and the problem to be solved by the present invention;

FIG. 7 is a view used for explaining prior art and the problem to be solved by the present invention;

FIG. 8 is a view used for explaining prior art and the problem to be solved by the present invention;

FIG. 9 is a view used for explaining the operation of the compiler;

FIGS. 10A, 10B, and 10C are views showing the data structure and example contents of variable information computed by the variable information computing unit 121, and of the history of variable pairs generated by the execution-path intermediate code generating unit 122;

FIG. 11 is a control flow graph of a program converted by the program converter 120;

FIG. 12 shows execution-path intermediate code after instruction scheduling by an optimizer 12;

FIG. 13 is a control flow graph according to a modification 1 of the present invention;

FIG. 14 is a control flow graph according to a modification 2 of the present invention; and

FIG. 15 shows execution-path intermediate code after instruction scheduling by the optimizer 12 according to the modification 2.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Embodiment

According to one embodiment of the present invention, a compiler (i) reads a source program, (ii) performs a lexical analysis that is a process of breaking the source program into a sequence of symbols called “lexical tokens”, (iii) performs a syntactic analysis that is a process of building a syntactic tree structure based on the lexical tokens, (iv) generates, based on the syntactic tree structure, an intermediate program written in a specific intermediate language used by the compiler, (v) optimizes the intermediate program by, for example, instruction scheduling and allocates resources, such as registers, to variables, and (vi) converts the optimized intermediate program to an executable program.

Structure

FIG. 1 is a functional block diagram showing an overall structure of a compiler 1 according to the embodiment.

The compiler 1 is composed of such functional blocks as a syntax analyzer 11, an optimizer 12, a resource allocator 13, and an executable-code generator 14. Note that in the figures, the word “intermediated” is abbreviated as “int”.

Specifically, the compiler 1 is implemented by a computer system generally composed of a microprocessor, Read Only Memory (ROM), Random Access Memory (RAM), and a hard disk. The ROM or hard disk stores a computer program.

The functional blocks of the compiler 1 shown in FIG. 1 are implemented by the microprocessor executing the computer program. In addition, the RAM and hard disk are used to realize storage of information by the functional blocks and transfer of information between the functional blocks.

Hereinafter, a description is given to each functional block.

The syntax analyzer 11 reads a source program 51, performs a syntactic analysis to recognize the control structure of

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the source program 51, generates an intermediate program composed of lines of intermediate code, and stores the intermediate program within the compiler 1. The intermediate code is a representation of the source program having an equivalent control structure and generated using conditional branch instructions and labels.

The optimizer 12 includes a program converter 120. The optimizer 12 performs a control flow analysis and a dataflow analysis on the intermediate program generated by the syntax analyzer 11, and sends the analytical results to the program converter 120, which will be described later in detail. In addition, the optimizer 12 carries out optimization at the time when the program converter 120 converts the intermediate code to executable code.

The control flow analysis mentioned herein is a process of analyzing the control flow of the intermediate program in order to break the intermediate program into basic blocks. On the other hand, the dataflow analysis is a process of determining, for each variable occurs in the program, a section within which the variable is alive, variable definition points, and variable reference points.

Note that the terms “definition” of a variable and “reference” to a variable are used herein in the following meaning.

When a statement updates the value held by a variable, it is said that the statement defines the variable, and the statement is called a variable definition point. When a statement uses the value held by a variable, it is said that the statement refers to the variable, and the statement is called a variable reference point.

Next, a description is given to the program converter 120.

The program converter 120 is generally composed of a variable information computing unit 121, an execution-path intermediate code generating unit 122, a judgment intermediate code generating unit 123, a restoration intermediate code generating unit 124, and a branch intermediate code generating unit 125.

On receiving hot path information from a source external to the compiler 1, the program converter 120 stores the hot path information therein and performs program conversion of a subroutine that contains a hot path.

The hot path information is input by a user and indicates an execution path determined in advance by the user.

The variable information computing unit 121 computes liveness information and definition information for each basic block, based on the analytical results received from the optimizer 12. Using the liveness information, the definition information, and the hot path information, the variable information computing unit 121 derives path-entry variables, path-exit variables, replacement target variables, and restoration target variables. The thus derived replacement target variables are sent to the execution-path intermediate code generating unit 122, whereas the restoration target variables are sent to the restoration intermediate code generating unit 124.

Liveness information indicates, for each basic block generated according to the control flow analysis, variables that are alive at the entry point of the basic block (hereinafter “liveness information IN”) and at the exit point of the basic block (“hereinafter, “liveness information OUT”). More specifically, liveness information IN indicates variables referenced before being defined downstream from the entry point of each basic block, whereas liveness information OUT indicates variables referenced before being defined downstream from the exit point of each basic block. Definition information (hereinafter “definition information DEF”) indicates variables defined in each basic block.

A similar description of the liveness of variables is found in “Compilers: Principles, Techniques, and Tools” by A. V. Aho,

R. Sethi, and J. D. Ullman, published by Addison Wesley Publishing Company in 1986, and pp. 631-632 of its Japanese version "Compilers I and II" translated by Kenichi Harada, published by SAIENSU-SHA Co., Ltd. in 1990.

Path-entry variables are live variables at the entry point of the hot path, i.e. the variables indicated by liveness information IN of the first basic block on the hot path. Path-exit variables are live variables at the exit point of the hot path, i.e. the variables indicated by liveness information OUT of the last basic block on the hot path.

Replacement target variables are path-entry variables that are defined on the hot path. Restoration target variables are both replacement target variables and path-exit variables.

The execution-path intermediate code generating unit **122** reads the hot path information **52** stored in the program converter **120** and the intermediate program stored in the compiler **1**. The execution-path intermediate code generating unit **122** then generates execution-path intermediate code from a series of statements composing part of the read intermediate program corresponding to the hot path, by replacing identifiers of replacement target variables sent from the variable information computing unit **121**. The thus generated execution-path intermediate code is sent to the judgment intermediate code generating unit **123**.

Here, a description is given to the process of replacing the identifiers of replacement target variables.

The execution-path intermediate code generating unit **122** replaces the identifiers of replacement target variables with different identifiers that are not present in a variable table. Each time the variable replacement takes place, the execution-path intermediate code generating unit **122** pairs a replacement target variable with a variable used to replace the replacement target variable (hereinafter, such a pair of pre- and post-replacement variables is referred to as a "variable pair"), and stores the variable pair in the program converter **120**. Note that the variable table is generated through the lexical analysis by collecting information about the identifiers and types of all variables declared in the program. The variable table is stored within the compiler **1**.

The judgment intermediate code generating unit **123** generates judgment intermediate code that includes a branch condition for executing the hot path, by modifying branch instructions included in the execution-path intermediate code sent from the execution-path intermediate code generating unit **122**. The judgment intermediate code generating unit **123** then inserts the judgment intermediate code into the execution-path intermediate code, so that the judgment intermediate code is executed subsequently to the execution-path intermediate code excluding the branch instructions. The resulting execution-path intermediate code is stored within the program converter **120**.

The restoration intermediate code generating unit **124** generates, based on the restoration target variables sent from the variable information computing unit **121**, restoration intermediate code for restoring the identifiers of restoration target variables back to their original identifiers. The thus generated restoration intermediate code is stored within the program converter **120**.

The branch intermediate code generating unit **125** reads from the program converter **120** the judgment intermediate code inserted in the execution-path intermediate code to generate branch intermediate code. The branch intermediate code generated herein causes, subsequently to execution of the execution-path intermediate code, the restoration intermediate code to be executed if the branch condition of the judgment intermediate code is true, and the partial intermediate code to be executed if the branch condition is false. The

branch intermediate code generating unit **125** then inserts the branch intermediate code into the execution-path intermediate code, so that the branch intermediate code is executed subsequently to the judgment intermediate code. The resulting execution-path intermediate code is then stored within the program converter **120**.

The resource allocator **13** reads the entire intermediate code generated. At the time of generating executable code from the intermediate code, the resource allocator **13** carries out allocation of hardware resources such as registers and memory, based on the liveness information of variables occurring in the entire intermediate code.

After the resource allocation, the executable-code generator **14** converts the entire intermediate code to an executable program **53** written in a suitable machine language. The executable program **53** is then output to the outside of the compiler **1**.

Data

Now, a description is given to data used by the compiler **1** of the embodiment.

FIG. **10A** shows liveness information IN **302**, liveness information OUT **304**, and definition information DEF **303** computed by the variable information computing unit **121** for each basic block of the control flow graph shown in FIG. **5B**.

FIG. **10B** shows path-entry variables **401**, path-exit variables **402**, replacement target variables **403**, and restoration target variables **404** derived by the variable information computing unit **121** based on the information shown in FIG. **10A**.

FIG. **10C** shows generation history of variable pairs for each basic block of the control flow graph shown in FIG. **9**. As mentioned above, each variable pair is generated by the execution-path intermediate code generating unit **122** when replacing a replacement target variable. The control flow graph shown in FIG. **9** represents the execution path newly generated by the execution-path intermediate code generating unit **122** by duplicating the statements residing on the hot path **200** shown in FIG. **5B** and conducting the variable replacement processing on the duplicate statements.

Operation

Next, with reference to the operation flow shown in FIG. **2**, a description is given mainly to operations of the program converter **120** where a characterizing feature of the present invention lies.

Note that in this embodiment, the program converter **120** processes a subroutine, which is referred to as a partial program. The subroutine includes multiple execution paths sharing a single entry point and a single exit point.

First, the syntax analyzer **11** syntactically analyzes a partial program upon receipt, generates partial intermediate code corresponding to the partial program, and stores the thus generated partial intermediate code within the compiler **1**. (Step **11**)

Next, at an input of the hot path information **52** (FIG. **1**), the program converter **120** stores therein the hot path information. (Step **12**) Subsequently to the step **12**, the optimizer **12** reads the partial intermediate code, performs a control flow analysis and dataflow analysis to produce and send analytical results to the variable information computing unit **121**. Based on the analytical results, the variable information computing unit **121** computes, for each basic block of the partial program, liveness information IN and OUT and definition information DEF. (Step **13**)

Next, based on the liveness information IN and OUT and definition information DEF computed in the step **13** as well as the hot path information received in the step **12**, the variable information computing unit **121** derives path-entry variables,

path-exit variables, replacement target variables, and restoration target variables. The variable information computing unit **121** sends the replacement target variables to the execution-path intermediate code generating unit **122** and the restoration target variables to the restoration intermediate code generating unit **124**. (Step **14**)

Subsequent to the step **14**, the execution-path intermediate code generating unit **122** reads the hot path information and the partial intermediate code, duplicates statements corresponding to the hot path of the partial intermediate code, and modifies the duplicate statements by replacing the identifiers of replacement target variables to generate execution-path intermediate code. The thus generated execution-path intermediate code is sent to the judgment intermediate code generating unit **123**. (Step **15**)

On receiving the execution-path intermediate code, the judgment intermediate code generating unit **123** generates judgment intermediate code by modifying branch conditions included in the execution-path intermediate code into a branch condition for executing the hot path. The judgment intermediate code generating unit **123** then inserts the judgment intermediate code into the execution-path intermediate code, so that the judgment intermediate code is executed subsequently to the statements of the execution-path intermediate code except the branch instructions. The resulting execution-path intermediate code is stored within the program converter **120**. (Step **16**)

Next, the restoration intermediate code generating unit **124** generates restoration intermediate code for restoring the restoration target variables received from the variable information computing unit **121**, and stores the restoration intermediate code within the program converter **120**. (Step **17**)

Subsequent to the step **17**, the branch intermediate code generating unit **125** reads the execution-path intermediate code stored in the step **16**, generates branch intermediate code, and inserts the branch intermediate code into the execution-path intermediate code. The branch intermediate code generated herein causes, subsequently to execution of the judgment intermediate code, the partial intermediate code generated in the step **11** to be executed from the beginning of the partial intermediate code if the branch condition of the judgment intermediate code is not met. If the branch condition is met, the restoration intermediate code generated in the step **17** is caused to be executed subsequently to the judgment intermediate code. (Step **18**)

The optimizer **12** reads the partial intermediate code stored in the step **11**, the execution-path intermediate code stored in the step **16**, and the restoration intermediate code stored in the step **17**, and optimizes all the read intermediate code. (Step **19**)

Variable Information Computing Processing

Next, a description is given to the variable information computing processing, with reference to FIG. **3**.

First, the optimizer **12** performs the control flow and data-flow analyses on the partial program (Step **21**). Based on the analytical results, the variable information computing unit **121** computes liveness information IN and OUT and definition information DEF relating to variables occurring in the partial program (Step **22**).

Next, the variable information computing unit **121** derives path-entry variables from the liveness information IN computed in the step **22** for the first block on the hot path, and path-exit variables from the liveness information OUT computed in the step **22** for the last block on the hot path (Step **23**).

Subsequent to the step **23**, the variable information computing unit **121** derives, as replacement target variables, the

path-entry variables that are indicated by the definition information DEF relating to the hot path (Step **24**).

Next, the variable information computing unit **121** derives, as restoration target variables, variables that are both the replacement target variable derived in the step **24** and the path-exit variables. The variable information computing unit **121** then sends the restoration target variables and the replacement target variables to the execution-path intermediate code generating unit **122** (Step **25**).

Variable Replacement Processing

On receiving information indicating the replacement target variables from the variable information computing unit **121**, the execution-path intermediate code generating unit **122** reads the partial intermediate code and the hot path information, duplicates statements corresponding to the hot path of the partial intermediate code, repeats the variable replacement processing on each replacement target variable included in the duplicate statements, and generates variable pairs.

Hereinafter, a description is given to the variable replacement processing with reference to FIG. **4**.

The execution-path intermediate code generating unit **122** repeats the variable replacement processing for each replacement target variable included in the duplicate statements (Step **30**).

The execution-path intermediate code generating unit **122** judges whether a currently processed replacement target variable is referenced by any statement (Step **31**) and contained in the existing variable pairs (Step **32**). When both the judgments result in the affirmative (Step **31**: YES and Step **32**: YES), the execution-path intermediate code generating unit **122** modifies the statement by replacing the identifier of the replacement target variable with the identifier that is paired in a relevant variable pair (Step **33**), and then moves onto a step **34**. When any of the judgments in the steps **31** and **32** results in the negative (Step **31**: NO or Step **32**: NO), the processing simply moves onto the step **34**.

Next, the execution-path intermediate code generating unit **122** judges whether the currently processed replacement target variable is defined by any statement (Step **34**) and contained in the existing variable pairs (Step **35**). When both the judgments result in the affirmative (Step **34**: YES and Step **35**: YES), the execution-path intermediate code generating unit **122** deletes the variable pair that contains the replacement target variable (Step **36**), and moves onto a step **37**. When it is judged in the step **35** that there is no corresponding variable pair (Step **35**: NO), the processing simply moves onto the step **37**.

In the step **37**, the execution-path intermediate code generating unit **122** determines a variable to be used to replace the replacement target variable that is defined, and replaces the replacement target variable with the thus determined variable, and generates a new variable pair made up of the pre- and post-replacement variables.

Operation Examples

Next, a specific example is given to the operation flow shown in FIG. **2**, using the partial source program shown in FIG. **5A**. FIGS. **5B** and **9-12** are also referenced in the following description. In this example, it is assumed that the intermediate code is relatively close to the source program.

In the step **11**, the syntax analyzer **11** syntactically analyzes the partial program and generates partial intermediate code. The thus generated partial intermediate code is stored within the compiler **1**.

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Next, in the step 12, the program converter 120 receives hot path information that specifies, as a hot path, a path 200 sequentially connecting the basic blocks B1, B2, B4, B5, and B7 shown in the control flow graph (FIG. 5B). Upon receipt, the program converter 120 stores therein the hot path information.

In the step 13, the optimizer 12 carries out the control flow and data flow analyses. Based on the analyses, the variable information computing unit 121 computes liveness information IN and OUT and definition information DEF (FIG. 10A) for each of the basic blocks B1-B7 of the control flow graph (FIG. 5B). Specifically, the liveness information IN for the basic block B1 (FIG. 5B) indicates the variables that are shown in FIG. 10A in the "IN" column 302 at the row "B1". The liveness information OUT for the basic block B1 indicates the variables that are shown in the "OUT" column 304 at the same row. The definition information DEF for the basic block B1 indicates the variables that are shown in the "DEF" column 303 at the same row.

Next, in the step 14, the variable information computing unit 121 derives the path-entry variables 401, the path-exit variables 402, the replacement target variables 403, and the restoration target variables 404 (FIG. 10B), based on the liveness information and definition information shown in FIG. 10A as well as on the hot path information input in the step 12.

The path-entry variables 401 are alive at the entry point of the hot path. In other words, the path-entry variables are indicated by the liveness information IN for the basic block B1 (FIG. 5B) and thus contained in the IN column 302 at the row "B1" (FIG. 10A).

The path-exit variables 402 are alive at the exit point of the hot path. In other words, the path-exit variables 402 are indicated by the liveness information OUT for the basic block B7 (FIG. 5B) and thus contained in the OUT column 304 at the row "B7" (FIG. 10A).

The replacement target variables 403 are the path-entry variables 401 that are contained in the DEF column 303 (FIG. 10A) for the basic blocks B1, B2, B4, B5, and B7 residing on the hot path 200.

The restoration target variables 404 are included in both the path-exit variables 402 and the replacement target variables 403.

In the example shown in FIG. 10, the DEF column 303 contains the variables {a, c, d, f, x}, whereas the path-entry variables are {b, c, d, e, g, z, w, y}. Consequently, the replacement target variables are {c, d}. In addition, the path-exit variables are {a, c, e, f, z, w, x, y}. Consequently, there is one restoration target variable, which is {c}.

The variable information computing unit 121 sends the replacement target variables to the execution-path intermediate code generating unit 122 and the restoration target variable to the restoration intermediate code generating unit 124.

In the next step of S15, the execution-path intermediate code generating unit 122 reads the partial intermediate code and the hot path information, duplicates the statements S1-S15 residing on the hot path 200 shown in FIG. 5, and generates new basic blocks B12-B72 with the duplicate statements. The execution-path intermediate code generating unit 122 then performs the variable replacement processing to replace the replacement target variables that are included in the duplicate statements and generates variable pairs. FIG. 9 shows the execution path that is newly generated by conducting the variable replacement processing on the duplicate statements.

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Now, a description is given to the variable replacement processing (FIG. 4) taking the basic blocks B12 and B22 shown in FIG. 9, as an example.

Before the variable replacement processing, the duplicate statements included in the basic block B12 are identical to the statements included in the basic block B1 shown in FIG. 5B. The duplicate statement S12 in the basic block B12 has a reference to the variable "c", which is the replacement target variable (FIG. 4, Step 31: YES). Yet, there is no variable pair containing the variable "c" (FIG. 4, Step 32: NO), so that the execution-path intermediate code generating unit 122 does not replace the variable "c". In addition, the statement S12 does not define any replacement target variables (FIG. 4, Step 34: NO). Thus, the duplicate statement S22 is to be processed next. The execution-path intermediate code generating unit 122 judges that the duplicate statement S22 before the variable replacement processing defines the replacement target variable "c" (FIG. 4, Step 34: YES) and that there is no variable pair made up of the variable "c" (FIG. 4, Step 35: NO). Consequently, the execution-path intermediate code generating unit 122 modifies the statement S22 by replacing the identifier of variable "c" with "t1" which is contained neither in the variable table nor in the variable pairs and generates a new variable pair (c, t1) (FIG. 4, Step 37). The statement S32 to be processed next does not have any reference to a replacement target variable and does not define any replacement target variables. Thus, no variable replacement takes place. Next, the statement S42 included in the next basic block B22 is to be processed. (Note that the variable pairs having been generated through the variable replacement processing conducted on the basic block B12 are shown in FIG. 10C in a "variable pair generation history" column 502 at the row "B12".)

Subsequently, it is judged that the statement S42 before the variable replacement processing has a reference to the variable "c" (FIG. 4, step 31: YES) and that the variable pair (c, t1) is already present as shown in FIG. 10C in the column 502 at the "B12" row (FIG. 4, Step 32: YES). Thus, the execution-path intermediate code generating unit 122 modifies the statement S42 by replacing the variable "c" with "t1" (FIG. 4, Step 33). Next, it is judged that the statement S42 defines the replacement target variable "c" (FIG. 4, Step 34: YES) and that the variable pair (c, t1) is already present (FIG. 4, Step 35: YES). Thus, the execution-path intermediate code generating unit 122 deletes the variable pair (c, t1) (FIG. 4, Step 36), modifies the statement S42 by replacing the identifier of variable "c" with "t2", which is included neither in the variable table nor in the variable pairs, and generates a new variable pair (c, t2) (FIG. 4, Step 37).

FIG. 10C shows the variable pair generation history 500 having been stored through the variable replacement processing repeated by the execution-path intermediate code generating unit 122 for each statement up to S152 of the basic block B72.

The execution-path intermediate code generating unit 122 sends, to the restoration intermediate code generating unit 124, the variable pairs (c, t2) and (d, t3) shown in FIG. 10C at the row of which block 501 column indicates "B72". In addition, the execution-path intermediate code generating unit 122 sends the statements S12-S152 composing the execution-path intermediate code shown in FIG. 9 to the judgment intermediate code generating unit 123.

Next, in the step 16, the judgment intermediate code generating unit 123 converts the branch conditions S32 and S92 included in the received statements into a statement S201 of branch intermediate code (shown in FIG. 11 in a basic block B104) that includes a branch condition for executing the hot

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path. The judgment intermediate code generating unit **123** then generates the basic block **B104** that includes the statement **S201** and stores the resulting basic block **B104** within the program converter **120**.

Next, in the step **17**, the restoration intermediate code generating unit **124** generates a statement **S301** of restoration intermediate code for restoring the variable "t2" to "c", based on the restoration target variable {c} and the variable pair (c, t2) sent from the variable information computing unit **121**. The restoration intermediate code generating unit **124** then generates the basic block **B103** (FIG. 11) with the statement **S301** of the restoration intermediate code.

In the step **18**, the branch intermediate code generating unit **125** reads the basic block **B104** shown in FIG. 11 and generates branch intermediate code. The branch intermediate code generated herein causes the statement **S301** in the basic block **B103** to be executed if the judgment in the statement **S201** is true, and causes the series of statements starting from the statement **S1** in the basic block **B1** to be executed if the judgment is false. The branch intermediate code generating unit **125** then inserts the branch intermediate code into the execution-path intermediate code.

In the step **19**, the optimizer **12** optimizes the intermediate code generated through the processing up to the step **18** to improve the execution speed.

FIG. 12 shows the basic block **B124** generated by conducting instruction scheduling on the statements of the basic block **B104**. Note that the notation "/" in the figure represents that statements preceding and subsequent to the notation are processed in parallel.

Modification 1

According to the above embodiment, the judgment intermediate code generating unit **123** generates the branch instruction **S201** that includes a branch condition for executing the hot path, by connecting the branch conditions **S32** and **S92** shown in FIG. 9 using logical AND. Yet, as in a statement **S202** shown in FIG. 13, it is applicable to invert the branch conditions **S32** and **S92**.

In addition, it is applicable to make an arrangement as shown in FIG. 13, so that the partial program is executed as a subroutine and a path connecting newly generated basic blocks **B114** and **B103** is taken as a main execution path. For this purpose, the basic block **B114** is placed at a position immediately after the statement **S0** which is the last statement in the basic block **B0** immediately preceding the partial program. In addition, the basic block **B103** is placed at a position immediately before the statement **S17** which is the first statement in the basic block **B8** immediately following the partial program.

Hereinafter, with reference to FIG. 2, a description is given to processing to make the above arrangement.

Note that the intermediate code representing the statements placed before and after the partial program is stored in the program converter **120** in advance.

In the step **15**, the execution-path intermediate code generating unit **122** duplicates the statements **S1-S15** residing on the hot path **200** and carries out the variable replacement processing on the duplicate statements to generate the statements **S12-S152** (FIG. 9) composing the execution-path intermediate code.

The execution-path intermediate code generating unit **122** inserts the statements **S12-S152** (FIG. 9) at a position immediately after the statement **S0** and stores the resulting intermediate code into the program converter **120**. In addition, the

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execution-path intermediate code generating unit **122** sends the statements **S12-S152** to the judgment intermediate code generating unit **123**.

In the step **16**, the judgment intermediate code generating unit **123** inverts the branch conditions of the branch conditions **S32** and **S92** included in the received statements, and connects the inversed branch conditions to generate the judgment intermediate code. The judgment intermediate code generating unit **123** then stores the basic block **B114** composed of the statements **S12-S152** stored within the program converter **120** and the thus generated judgment intermediate code.

Next, in the step **17**, the restoration intermediate code generating unit **124** generates the basic block **B103** that includes the statement **S301** of the restoration intermediate code. In addition, the restoration intermediate code generating unit **124** places the basic block **B103** at a position immediately after the basic block **B114** stored in the program converter **120**, and places a series of statements starting from the statement **S17** at a position immediately after the basic block **B103**.

In the step **18**, the branch intermediate code generating unit **125** reads the basic block **B114** and generates branch intermediate code that causes a branch to the statement **S1** in the basic block **B1** if the branch condition of the judgment intermediate code is met. The thus generated branch intermediate code is inserted into the judgment intermediate code, whereby the statement **S202** is generated. The branch intermediate code generating unit **125** then generates the basic block **B114** that includes the statement **S202**, and stores the basic block **B114** within the program converter **120**.

In addition, the branch intermediate code generating unit **125** generates the statement **S16** of branch intermediate code that causes a branch from the statement **S15** to the statement **S17**. The branch intermediate code generating unit **125** then inserts the statement **S16** at a position immediately following the statement **S15**, and stores the resulting intermediate code within the program converter **120**.

As described above, the statements are reordered, so that the partial program is executed as a subroutine and that the execution-path code and the source program code except the partial program are taken as a main path. This arrangement eliminates a branch instruction causing a branch from the end of execution-path code to the source program. In the case where the execution-path code is expected to be executed with a high frequency, memory allocation is effectively carried out, so that the execution speed of the overall main path is improved.

Modification 2

In the modification 1 described above, the judgment intermediate code generating unit **123** generates the statement **S202** by connecting the branch conditions **S3** and **S9**. Yet, it is also applicable to convert the branch instructions into separate sets of judgment intermediate code as the branch conditions **S202** and **S203** shown in FIG. 14.

In this case, in the step **16**, the judgment intermediate code generating unit **123** inverts the branch conditions of the branch conditions **S32** and **S92**, converts the inverted statements into separate sets of judgment intermediate code.

In the step **18**, the branch intermediate code generating unit **125** generates separate sets of branch intermediate code each causing a branch to the statement **S1** at the top of the basic block **B1** when the respective branch condition of each set of judgment intermediate code corresponding to respective one of the statements **S32** and **S92** is true. The branch intermediate code generating unit **125** then inserts the sets of branch

intermediate code into the respective sets of judgment intermediate code to generate statements S202 and S203. Finally, the branch intermediate code generating unit 125 generates a basic block B134 and stores the basic block B134 within the program converter 120.

FIG. 15 shows the example of the intermediate code of which statements in the basic block B144 have been optimized in the step 19 by the optimizer 12 using the instruction scheduling.

As shown in FIG. 15, the judgment intermediate code and branch intermediate code are generated separately for each branch conditions. Thus, a judgment as to whether the hot path is taken is made earlier. This arrangement causes another path to be taken earlier when the hot path is not taken. This arrangement is especially effective when the hot path is not expected to be taken very frequently.

Supplemental Note

Up to this point, a compiler according to the present invention has been described by way of the embodiment and modifications. It should be naturally appreciated, however, that the present invention is not limited to the above specific embodiment and modifications.

(1) According to the above embodiment, the program converter 120 carries out the variable replacement processing by first duplicating the statements of the intermediate code corresponding to the hot path and then replacing the replacement target variables included in the duplicate statements. Yet, the variable replacement processing may be carried out by sequentially referencing the statements and generates execution-path intermediate code, without involving duplication of the statements.

(2) According to the variable replacement processing in the above embodiment, when a replacement target variable is defined, the variable at the variable definition point is replaced, and a variable pair is replaced for each variable replaced. In addition, when a replacement target variable is referenced, the variable at the variable definition point is replaced with an identifier as shown in a corresponding variable pair. Yet, it is also applicable to replace a replacement target variable at the variable definition point and the variable reference point all with the same identifier.

(3) According to the above embodiment, the hot path information is input by a user to the program converter 120. However, there is an alternative in the case where the compiler has an interpreter function of sequentially interpreting and executing a program or where the compiler operates in conjunction with a device capable of executing a program such as a debugger. In such a case, it is applicable to sequentially execute the source program and dynamically store information relating to execution paths having been taken in memory or other storage. The program converter 120 uses the stored information to extract frequently taken execution paths.

(4) According to the above embodiment, the program converter 120 generates an executable program by converting intermediate program that has been converted by the syntax analyzer 11 and subjected to the variable replacement processing. However, it is also applicable to conduct the variable replacement processing on the source program statements residing on the hot path, and then converts the resulting source program into an executable program.

(5) The present invention may be embodied as computer programs executed by a computer to carry out the various processing described above. Further, the present invention may be embodied as digital signals representing the computer programs. The present invention may be embodied as a computer-readable recording medium storing any of the programs

and digital signals. The computer-readable recording medium may be a flexible disk, a hard disk, a CD-ROM, an MO disc, a DVD, or a semiconductor memory. Alternatively, the present invention may be embodied as any of the computer programs and digital signals transmitted via a network, such as an electronic communications network, a wired or wireless communications network, or the Internet.

Although the present invention has been fully described by way of examples with reference to the accompanying drawings, it is to be noted that various changes and modifications will be apparent to those skilled in the art. Therefore, unless such changes and modifications depart from the scope of the present invention, they should be construed as being included therein.

What is claimed is:

1. A compiler apparatus including a microprocessor for converting a source program including a branch instruction into an object program composed of lines of object code, the apparatus comprising:

an execution path specifying unit configured to specify one of a plurality of execution paths of a partial series of instructions, including a branch instruction, of the source program;

an execution-path code generating unit configured to generate execution-path code that is object code corresponding to instructions residing on the specified execution path except the branch instruction, with replacing each specific variable residing on the specified execution path with another variable which does not reside on the specified execution path, wherein the specific variable is a variable that needs to be alive at an entry point of the specified execution path and is defined on the specified execution path;

a restoration code generating unit configured to generate restoration code for restoring each of the replaced variables that needs to be alive at an exit point of the specified execution path to an original variable;

a partial code generating unit configured to generate partial code corresponding to the partial series of instructions;

a branch code generating unit configured to generate branch code based on a branch condition of the branch instruction residing on the specified execution path; and an optimizer configured to optimize the execution-path code to improve execution speed, wherein

the branch code leads from an end of the execution-path code to a beginning of the restoration code if the branch condition is true, and leads from the end of the execution-path code to a beginning of the partial code if the branch condition is false so that the partial code including branch instruction is executed after end of execution of the execution-path code.

2. The compiler apparatus according to claim 1, wherein: the execution-path code generating unit is further configured to place the execution-path code at a position immediately after a series of instructions immediately preceding a beginning of the partial series of instructions,

the restoration code generating unit is further configured to place the restoration code at a position immediately after the end of the execution-path code and to place, at a position immediately after the restoration code, a series of instructions immediately following an end of the partial series of instructions, and

the branch code generating unit is further configured to generate branch code that causes a branch from an end of the partial code to the series of instruction immediately following the end of the partial series of instructions.

3. The compiler apparatus according to claim 2, wherein: the compiler apparatus converts the source program into intermediate code based on a syntactic analysis, and converts the intermediate code into the object program, the execution-path code generating unit includes: 5

- a variable information deriving subunit operable configured to derive a target variable to be replaced, from variables included in partial intermediate code that is converted from the partial series of instructions based on the syntactic analysis; 10
- an execution-path intermediate code generating subunit configured to generate execution-path intermediate code at least including intermediate code that is included in the partial intermediate code and corresponds to the instructions residing on the specified execution path except the branch instruction, by replacing each target variable included in the intermediate code with another variable; and 15
- a judgment intermediate code generating subunit configured to convert all branch condition included in the execution-path intermediate code into a single branch condition for taking the specified execution path and to generate judgment intermediate code for making a judgment on the branch condition, 20

the restoration code generating unit includes: 25

- a restoration intermediate code generating subunit configured to generate restoration intermediate code for restoring each replaced variable that needs to be alive at the exit point of the specified execution path to an original variable, and 30

the branch code generating unit includes:

- a branch intermediate code generating subunit configured to generate branch intermediate code that causes a branch to a beginning of the partial intermediate code if the branch condition in the judgment intermediate code is false; and 35
- an executable code generating subunit configured to convert the partial intermediate code, the execution-path intermediate code, the judgment intermediate code, the restoration intermediate code, and the branch intermediate code to executable code that constitutes the object program. 40

4. The compiler apparatus according to claim 2, wherein: the compiler apparatus converts the source program into intermediate code based on a syntactic analysis, and converts the intermediate code into the object program, the execution-path code generating unit includes: 45

- a variable information deriving subunit configured to derive a target variable to be replaced, from variables included in partial intermediate code that is converted from the partial series of instructions based on the syntactic analysis; 50
- an execution-path intermediate code generating subunit configured to generate execution-path intermediate code at least including intermediate code that is included in the partial intermediate code and corresponds to the instructions residing on the specified execution path except the branch instruction, by replacing each target variable included in the intermediate code with another variable; and 55
- a judgment intermediate code generating subunit configured to separately convert each branch condition included in the execution-path intermediate code into an individual branch condition for taking the specified execution path and to generate separate sets of judgment intermediate code each for making a judgment on a respective one of the branch conditions, 60

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the restoration code generating unit includes:

- a restoration intermediate code generating subunit configured to generate restoration intermediate code for restoring each replaced variable that needs to be alive at the exit point of the specified execution path to an original variable, and

the branch code generating unit includes:

- a branch intermediate code generating subunit configured to separately generate sets of branch intermediate code each for causing a branch to a beginning of the partial intermediate code if the branch condition in the respective one of the sets of judgment intermediate code is false and leading toward a beginning of the restoration intermediate code if the branch condition is true; and

an executable code generating subunit configured to convert the partial intermediate code, the execution-path intermediate code, the judgment intermediate code, the restoration intermediate code, and the branch intermediate code to executable code that constitutes the object program.

5. The compiler apparatus according to claim 1, wherein: the compiler apparatus has an interpreter function for sequentially executing the source program, the compiler apparatus further comprises:

- an extracting unit configured to extract a frequently executed path by collecting information on execution paths taken during execution of the partial series of instructions using the interpreter function, and

the execution path specifying unit specifies the execution path extracted by the extracting unit.

6. The compiler apparatus according to claim 1, wherein the compiler apparatus further optimizes object code generated by the partial code generating unit, the restoration code generating unit, and the branch code generating unit.

7. A compilation method for converting a source program containing a branch instruction into an object program composed of lines of object code, the method comprising the steps of:

- specifying one of a plurality of execution paths of a partial series of instructions, including a branch instruction, of the source program;
- generating execution-path code that is object code corresponding to instructions residing on the specified execution path except the branch instruction, with replacing each specific variable residing on the specified execution path with another variable which does not reside on the specified execution path, wherein the specific variable is a variable that needs to be alive at an entry point of the specified execution path and is defined on the specified execution path;
- generating restoration code for restoring each of the replaced variables that needs to be alive at an exit point of the specified execution path to an original variable;
- generating partial code corresponding to the partial series of instructions;
- generating branch code based on a branch condition of the branch instruction residing on the specified execution path; and
- optimizing the execution-path code to improve execution speed, wherein

the branch code leads from an end of the execution-path code to a beginning of the restoration code if the branch condition is true, and leads from the end of the execution-path code to a beginning of the partial code if the

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branch condition is false so that the partial code including branch instruction is executed after end of execution of the execution-path code.

8. The compilation method according to claim 7, wherein the execution-path code generating step further involves placing the execution-path code at a position immediately after a series of instructions immediately preceding a beginning of the partial series of instructions, the restoration code generating step further involves placing the restoration code at a position immediately after the end of the execution-path code and placing, at a position immediately after the restoration code, a series of instructions immediately following an end of the partial series of instructions, and the branch code generating step further involves generating branch code for causing a branch from an end of the partial code to the series of instruction immediately following the end of the partial series of instructions.

9. The compilation method according to claim 8, wherein the compilation method converts the source program into intermediate code based on a syntactic analysis, and converts the intermediate code into the object program, the execution-path code generating step includes the sub-steps of:

deriving a target variable to be replaced, from variables included in partial intermediate code that is converted from the partial series of instructions based on the syntactic analysis;

generating execution-path intermediate code at least including intermediate code that is included in the partial intermediate code and corresponds to the instructions residing on the specified execution path except the branch instruction, by replacing each target variable included in the intermediate code with another variable; and

converting all branch condition included in the execution-path intermediate code into a single branch condition for taking the specified execution path and generating judgment intermediate code for making a judgment on the branch condition,

the restoration code generating step includes the substep of:

generating restoration intermediate code for restoring each replaced variable that needs to be alive at the exit point of the specified execution path to an original variable, and

the branch code generating step includes the substeps of: generating branch intermediate code that causes a branch to a beginning of the partial intermediate code if the branch condition in the judgment intermediate code is false; and

converting the partial intermediate code, the execution-path intermediate code, the judgment intermediate code, the restoration intermediate code, and the branch intermediate code to executable code that constitutes the object program.

10. The compilation method according to claim 8, wherein the compilation method converts the source program into intermediate code based on a syntactic analysis, and converts the intermediate code into the object program, the execution-path code generating step includes the sub-steps of:

deriving a target variable to be replaced, from variables included in partial intermediate code that is converted from the partial series of instructions based on the syntactic analysis;

generating execution-path intermediate code at least including intermediate code that is included in the

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partial intermediate code and corresponds to the instructions residing on the specified execution path except the branch instruction, by replacing each target variable included in the intermediate code with another variable; and

separately converting each branch condition included in the execution-path intermediate code into an individual branch condition for taking the specified execution path and generating separate sets of judgment intermediate code each for making a judgment on a respective one of the branch conditions,

the restoration code generating step includes the substep of:

generating restoration intermediate code for restoring each replaced variable that needs to be alive at the exit point of the specified execution path to an original variable, and

the branch code generating step includes the substeps of: separately generating sets of branch intermediate code each for causing a branch to a beginning of the partial intermediate code if the branch condition in the respective one of the sets of judgment intermediate code is false and leading toward a beginning of the restoration intermediate code if the branch condition is true; and

converting the partial intermediate code, the execution-path intermediate code, the judgment intermediate code, the restoration intermediate code, and the branch intermediate code to executable code that constitutes the object program.

11. The compilation method according to claim 7, wherein the compilation method sequentially executes the source program by interpreting,

the compilation method further comprises the substep of: extracting a frequently executed path by collecting information on execution paths taken during execution of the partial series of instructions using the interpreter function, and

the execution path specifying step specifies the execution path extracted in the extracting step.

12. The compilation method according to claim 7, wherein the compilation method further optimizes object code generated in the partial code generating step, the restoration code generating step, and the branch code generating step.

13. A computer-readable recording medium comprising a compilation program for causing a device including a CPU to convert a source program containing a branch instruction into an object program composed of lines of object code, the compilation program composed of instructions, when executed, to cause the device to perform the steps of:

specifying one of a plurality of execution paths of a partial series of instructions, including a branch instruction, of the source program;

generating execution-path code that is object code corresponding to instructions residing on the specified execution path except the branch instruction, with replacing each specific variable residing on the specified execution path with another variable which does not reside on the specified execution path, wherein the specific variable is a variable that needs to be alive at an entry point of the specified execution path and is defined on the specified execution path;

generating restoration code for restoring each of the replaced variables that needs to be alive at an exit point of the specified execution path to an original variable;

generating partial code corresponding to the partial series of instructions;

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generating branch code based on a branch condition of the branch instruction residing on the specified execution path; and

optimizing the execution-path code to improve execution speed, wherein

the branch code leads from an end of the execution-path code to a beginning of the restoration code if the branch condition is true, and leads from the end of the execution-path code to a beginning of the partial code if the branch condition is false so that the partial code including branch instruction is executed after end of execution of the execution-path code.

14. The computer-readable recording medium according to claim **13**, wherein:

the execution-path code generating step further involves placing the execution-path code at a position immediately after a series of instructions immediately preceding a beginning of the partial series of instructions,

the restoration code generating step further involves placing the restoration code at a position immediately after the end of the execution-path code and placing, at a position immediately after the restoration code, a series of instructions immediately following an end of the partial series of instructions, and

the branch code generating step further involves generating branch code that causes a branch from an end of the partial code to the series of instruction immediately following the end of the partial series of instructions.

15. The computer-readable recording medium according to claim **14**, wherein:

the compilation program further causes the device to convert the source program into intermediate code based on a syntactic analysis, and converts the intermediate code into the object program,

the execution-path code generating step includes the substeps of:

deriving a target variable to be replaced, from variables included in partial intermediate code that is converted from the partial series of instructions based on the syntactic analysis;

generating execution-path intermediate code at least including intermediate code that is included in the partial intermediate code and corresponds to the instructions residing on the specified execution path except the branch instruction, by replacing each target variable included in the intermediate code with another variable; and

converting all branch condition included in the execution-path intermediate code into a single branch condition for taking the specified execution path and generating judgment intermediate code for making a judgment on the branch condition,

the restoration code generating step includes the substep of:

generating restoration intermediate code for restoring each replaced variable that needs to be alive at the exit point of the specified execution path to an original variable, and

the branch code generating step includes the substeps of: generating branch intermediate code that causes a branch to a beginning of the partial intermediate code if the branch condition in the judgment intermediate code is false; and

converting the partial intermediate code, the execution-path intermediate code, the judgment intermediate code, the restoration intermediate code, and the

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branch intermediate code to executable code that constitutes the object program.

16. The computer-readable recording medium according to claim **14**, wherein:

the compilation program further causes the device to convert the source program into intermediate code based on a syntactic analysis, and converts the intermediate code into the object program,

the execution-path code generating step includes the substeps of:

deriving a target variable to be replaced, from variables included in partial intermediate code that is converted from the partial series of instructions based on the syntactic analysis;

generating execution-path intermediate code at least including intermediate code that is included in the partial intermediate code and corresponds to the instructions residing on the specified execution path except the branch instruction, by replacing each target variable included in the intermediate code with another variable; and

separately converting each branch condition included in the execution-path intermediate code into an individual branch condition for taking the specified execution path and generating separate sets of judgment intermediate code each for making a judgment on a respective one of the branch conditions,

the restoration code generating step includes the substep of:

generating restoration intermediate code for restoring each replaced variable that needs to be alive at the exit point of the specified execution path to an original variable, and

the branch code generating step includes the substeps of:

separately generating sets of branch intermediate code each for causing a branch to a beginning of the partial intermediate code if the branch condition in the respective one of the sets of judgment intermediate code is false and leading toward a beginning of the restoration intermediate code if the branch condition is true; and

converting the partial intermediate code, the execution-path intermediate code, the judgment intermediate code, the restoration intermediate code, and the branch intermediate code to executable code that constitutes the object program.

17. The computer-readable recording medium according to claim **13**, wherein:

the compilation program further causes the device to sequentially execute the source program by interpreting, the compilation program further causes the device to perform the substep of:

extracting a frequently executed path by collecting information on execution paths taken during execution of the partial series of instructions using the interpreter function, and

the execution path specifying step specifies the execution path extracted in the extracting step.

18. The computer-readable recording medium according to claim **13**, wherein

the compilation program further causes the device to optimize object code generated in the partial code generating step, the restoration code generating step, and the branch code generating step.